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Wind energy resource in Northern Mexico

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ABSTRACT

Mexico has installed less wind power compared to the other North American countries. Renewable energy sources only account for 3% of the energy mix in Mexico. The U.S. states bordering Mexico, namely Texas, New Mexico, Arizona, and California, have good wind power resources. Among them, Texas has the highest installed wind power capacity of 10.34 GW. The wind resources in these bordering states indicate that the wind energy resource in Northern Mexico must be assessed; thus, the spatial and temporal information about the wind energy resource was studied. The daily pattern of the wind speed, one per state studied, was obtained. The wind speed was found to exhibit a pattern; it increases from 4 pm until 6 am the following day. The main conclusions are that the state of Tamaulipas has the highest Wind Power Density (WPD) of 1000 W/m^2 during September and October, but the north of Nuevo Leon has, in a large part of its territory, an annual WPD greater than 103 W/m^2; each state has 1700 useful hours of wind speed above 3 m/s. Northern Mexico has some zones with excellent wind speed as well; the states of Chihuahua, Coahuila, Nuevo Leon and Tamaulipas have a wind speed of over 4.51 m/s across nearly their entire territories. Because Mexico in recent years has been starting to exploit renewable energy sources, the government has mandated energy reform, which improves the conditions for investment in wind energy in Mexico.

Contents

1. Introduction

Energy is a vital input for social and economic development [1]. As a result of the globalisation of human activities, the demand for energy has increased remarkably, especially in emergent

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Nomenclature

SMN	Servicio Meteorológico Nacional
AMS	Automatic Meteorological Stations
INIFAP	Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias
SMSEN	Surface Meteorology and Solar Energy of National
ASDC	Atmospheric Science Data Center
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
LCE	Life Cycle Environmental
WRA	Wind Resource Assessment
OK	Ordinary Kriging
UK	Universal Kriging
ρ	Correlation coefficient (Pearson)
σ_{ij}	Covariance between series i and j
σ_i	Standard deviations of series i
WPD	Wind Power Density
P	Wind Power Density (Eq. 2)
$\overline{P}$	Wind power density Average
P_W	Power output
PDF	Probability Density Function
d	Air density (1.225 kg/m^3)
v	Wind speed (m/s).

countries due to their industrial growth. Because the fossil fuel resources required for the generation of energy are becoming scarce and the carbon emissions to the atmosphere from the burning of such fossil fuel resources is related to climate change, the interest in energy savings and environmental protection has increased [2]. Experts predict that the world will require 30 TW of energy resources by the year 2050 to maintain the current economic growth [3]. One strategy to reduce the dependence on fossil fuel resources involves using renewable energy sources [4], not only for large-scale energy production but also for stand-alone systems [5]; wind power has the potential to satisfy both types of systems [6].

Renewable energy can contribute to social and economic development, energy access, energy security, energy independency and the reduction of the negative impacts on the environment and health of fossil fuel-based energy [7]. Renewable energy policy and research worldwide have driven the growth of these technologies with good results [8], e.g., in the European Union (EU) [9], the United States of America (USA) and China [10].

According to the report of the International Energy Agency (IEA) [11], the distribution of global electricity generation in terms of resource utilisation is petroleum products 5.6%, natural gas 20.9%, coal 41.5%, nuclear power 13.8%, hydraulic power 15.6%, and other resources 2.6%.

Deployment of a 100% renewable energy system is expected to be technically and economically feasible in the future [12]. Some agencies (European Wind Energy Association and the German Aerospace Center) have proposed scenarios that have renewable energy sources, including wind farms, supplying 80% of Europe's entire electricity demand by 2050. The National Renewable Energy Laboratory in the USA assessed how wind could supply 20% of the entire US electricity demand by 2030 [13]. Another study [14] demonstrated that the wind electricity potential in Canada is many times the current total electricity demand.

North American countries currently have the following wind power installed capacity: USA (47 GW), Canada (5.27 GW), and Mexico (0.57 GW) [7]. The USA states bordering Mexico are Texas, New Mexico, Arizona and California. Among all of the US states, Texas has the highest installed capacity of 10.34 GW, followed by Iowa (4.32 GW) and California (3.93 GW). Lesser installed capacities are in New Mexico (750 MW) and Arizona (138 MW). During 2003, in the state of Arizona, a set of high-resolution wind energy maps were produced for evaluating the most promising sites for wind development [15].

In Mexico, a total energy production of 257.9 TW/h has been determined, which is distributed as follows: 205.1 fossil fuels, 35.8 hydroelectric, 10.1 nuclear, 6.5 geothermal, and 0.4 wind [16]. The new law of Mexico mandates that CO_2 emissions must be reduced by 30% from business-as-usual levels by 2020 and by 50% by 2050 from the year 2000 levels [15]. Mexico has many forms of renewable energy resources: ocean energy [17], hydroelectric [18], geothermal [19], biomass [20], wind [21,22] and solar [23]. Renewable energy projects have enormous potential to satisfy the energy consumption in Mexico, not only because of the abundant renewable resources but also because of the emission reduction opportunities that could be realised through industrial projects, similar to those projects that have been successful in Asia [24].

The first step for wind power implementation is performing a wind resource assessment (WRA), both spatially and temporally throughout the day and months of at least two years. Much information exists regarding WRA in the literature: Khalid Farooq and Kumar [25] estimated the current and future potential of renewable energy sources for power generation by employing new technologies; Millward-Hopkins [26] developed an analytical methodology for predicting above-roof mean wind speeds in urban areas and used the methodology to map wind speeds over four different UK cities; Wu et al. [27] used statistical methods involving three probability density functions, i.e., two-parameter Weibull, Logistic and Lognormal, to perform wind speed distribution modelling using data measured at a typical site in Inner Mongolia, China; Saleh et al. [28] assessed the wind resource using different methods to estimate the Weibull distribution parameters for the wind speed; Durisic and Mikulovic [29] analysed data, wind speed and direction, average wind speed and power density, and Weibull distribution parameters (c and k) to perform a WRA; Gormally et al. [30] used GIS-based techniques to develop a methodology that assesses the regional-scale potential for community-based renewable electricity; Lee et al. [31] assessed the potential of offshore wind power generation at Younggwang in Korea, which is a candidate site of the offshore wind farm planned to be completed in 2019; in Masdar City, the wind speed was assessed by Isam et al. [32] using the inferred vertical wind profile, which was adequately fitted with a power law profile; Girard et al. [33] quantified the impact on market revenue of the predictability and the capacity factor of a wind farm or a cluster of wind farms. WRA has been useful to determine the techno-economic potential of wind turbine generator sites in Malaysia with light winds, as reported by Nor et al. [34].

Regarding the life cycle environmental (LCE) impacts of wind power, Arvensen and Hertwich [35] indicated that the current body of LCE impacts of wind power provides a fairly good overall understanding of fossil energy use and its associated pollution. WRA has been used to assess electricity options: Stamford and Azapagic [36] used an LCE impact assessment to identify the most sustainable options and to inform policy; Sungmoon et al. [37] proposed a new Bayesian approach to estimate the annual energy production (AEP) of a site, for which construction of wind turbines is considered. However, wind discontinuity is one of the factors that significantly affects the installation of wind farms. Several studies indicate how the interconnection of large, geographically

dispersed wind farms could reduce the variability in the aggregate electrical power output from 30% to 60% in Europe [38] and the USA [39] compared to that of a single wind farm.

Although there have been studies of the global wind resource assessment in Mexico [21,39,40] at a height of 10 metres, it is important to analyse the wind resource at the greatest detail possible at a height of 50 metres and in geographic areas as broadly as possible. Wind has been studied as an energy resource in different geographic areas in Mexico. The onshore wind resource at the North of the Yucatan Peninsula was studied through the implementation of a network of ultrasonic wind sensors [41], along with the study of the short-term [42] and long-term [43] wind characteristics; in addition, the offshore wind resource was examined through the study of the wind profiles [44]. At Veracruz State, the wind speed was found to average between 5.45 m/s [45] and 6 m/s [46], and possible sites for a wind farm were determined, with the coastal areas identified to have the best properties of wind speed persistence [47]. For Oaxaca, several studies of wind forecasting were performed at the South Coast [48] and short-term wind speed forecasting was performed in La Venta [49]; the state of Oaxaca is especially interesting because a wind energy resource atlas of Oaxaca was produced by NREL in 2003 [50,51]. Other states have also been studied, e.g., wind speed periodicity in Chihuahua [52] and wind forecasting in Baja California Sur [53], Zacatecas and Quintana Roo [54].

Despite the fact that the border states of the USA are known to have great potential, with Texas being the state of the USA with the most wind power installed, wind energy has not been evaluated in detail in the northern states of Mexico. The aim of this work is to provide spatial and temporal (hourly and monthly) information on the wind energy resource at the Northern Mexican states, except at Baja California Norte.

2. Meteorological stations in northern Mexico

Northern Mexico has five states, Sonora, Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, which together comprise an area of 722,915.57 m^2 and represent 36.9% of the national territory [55].

Site-specific wind resource information is essential for the design details and the economic feasibility of wind projects [56]; in this study, data from 2009 and 2010 were taken from 31 Automatic Meteorological Stations (AMS) of the Servicio Meteorológico Nacional (SMN), Mexico [57], 184 meteorological station of the Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP), Mexico [58], and 22 points of the Surface Meteorology and Solar Energy of National (SMSEN) from the Atmospheric Science Data Center (ASDC) of the National Aeronautics and Space Administration (NASA) [59]. Fig. 1 shows the geographic position of the meteorological stations and the points selected in northern Mexico.

From Fig. 1, each state has been covered with meteorological stations and points from SMSEN. Table 1 summarises the number of stations and their sources in each Mexican state.

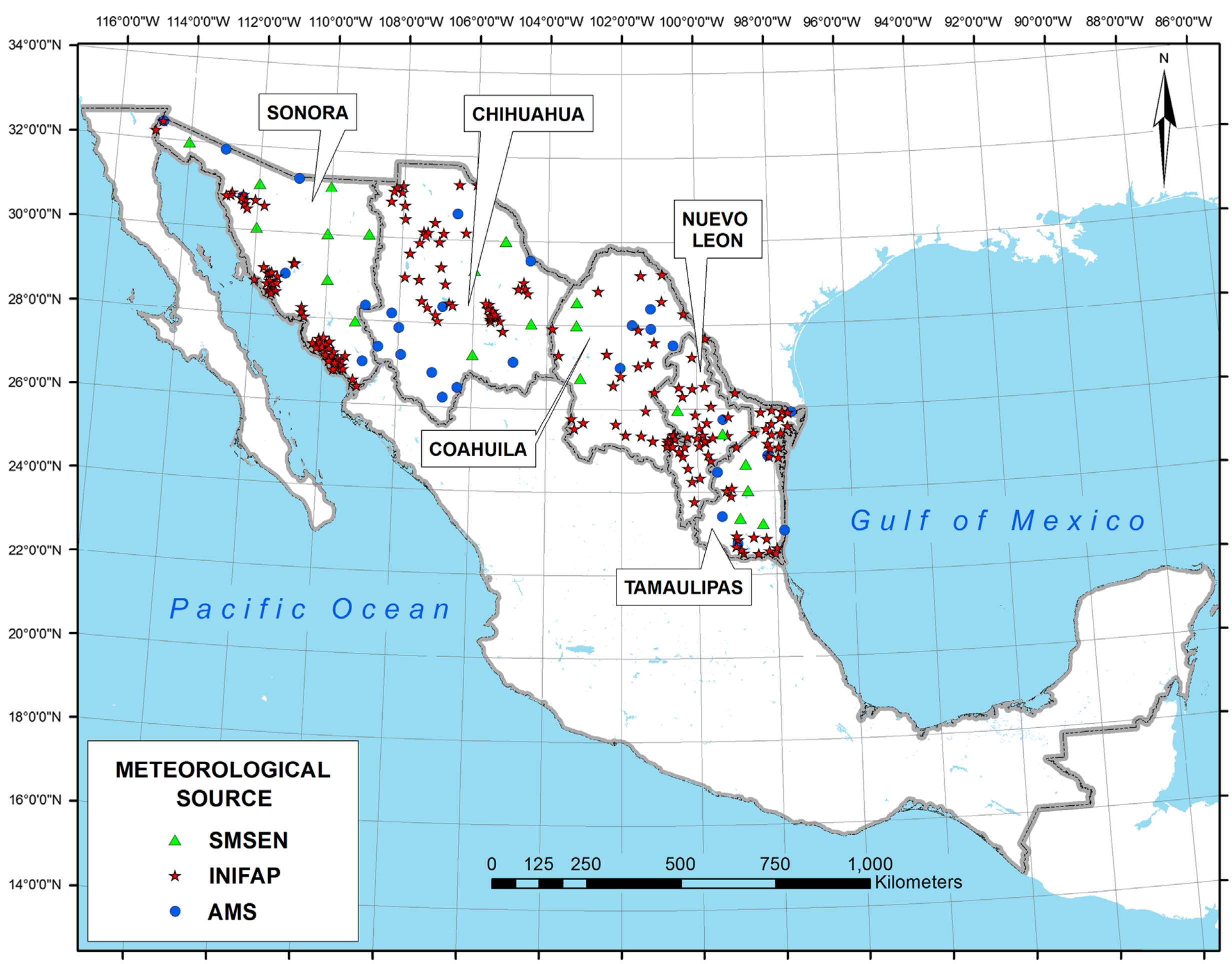

Fig. 1. Meteorological stations in northern Mexico.

Table 1
Meteorological stations.

State	Source			
	SMN	INIFAP	ASDC	Total
Chihuahua	12	43	4	59
Coahuila	5	25	3	33
Nuevo León	1	32	2	35
Sonora	7	55	8	70
Tamaulipas	6	29	5	40
Total	31	184	22	**237**

Table 2
Correlation coefficient (ρ) between SMSEN and AMSs data.

SMSEN	ρ (%)	AMS
Point_1	89	Sonoyta
Point_2	91	Nogales
Point_4	87	Nogales
Point_6	92	Nogales
Point_8	95	Yecora
Point_9	80	Ojinaga
Point_11	87	Guachochi
Point_17	98	El Cuch
Point_18	83	Villagran
Point_20	89	Juamave
Point_21	87	B del Tordo

Table 3
Correlation coefficient (ρ) between SMSEN and INIFAP data.

SMSEN	ρ (%)	INIFAP
Point_1	90	Moc
Point_2	93	Cand
Point_3	86	Can
Point_5	80	Oji
Point_7	88	Cuesta
Point_9	83	Oas
Point_10	95	Sta
Point_12	93	RSM
Point_13	97	RLP
Point_14	86	RSM
Point_15	82	ESC32
Point_16	85	Mil
Point_17	83	Leo
Point_18	98	Barr
Point_19	91	Btal
Point_21	95	CEA

2.1. Correlation between meteorological stations in northern Mexico

Most of the data fulfilled the control procedures; however, data from certain stations were removed. Next, the stability of wind speed was assessed through statistical analyses.

Data validation between fixed sensors data (AMS, INIFAP) and satellite data (SMSEN) was performed using a statistical correlation between the nearest meteorological stations and point selected. The correlation coefficient is calculated as a normalised way of giving the variance, and it is given by:

$$\rho = \frac{\sigma_{12}^2}{\sigma_1 \cdot \sigma_2} \tag{1}$$

A definition of the correlation coefficient was provided by Pearson, as expressed in Eq. 1, where ρ is the correlation, σ_{12} is the covariance between series 1 and 2, and σ_1 and σ_2 are the standard deviations of series 1 and 2, respectively (square roots of the variances).

The correlation coefficient between SMSEN points and AMSs data is presented in Table 2. The correlation coefficient exhibits a minimum correlation value of 83% (Villagran and Point_18), a maximum of 98% (Presa El Cuchillo and Point_17), and an average of these correlations of 89%. The nearest SMSEN and INIFAP stations were utilised to correlate their data. Table 3 presents the correlation coefficients between the stations. The analysis of this second correlation between satellite data and fixed sensors data indicates that the minimum of 80% was registered between Point_3 and the Ojinaga station, the maximum of 97% was registered between Point_13 and the RLP station, and the average of these second correlations is also 89%. The statistical relationship between the data provides confidence in their use in this work.

3. Wind Assessment in northern Mexico

3.1. Wind Speed

The north of Mexico has five states, Sonora, Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, each of which has a good wind resource [21]. However, the utilisation of wind energy in these states has been slow, partially due to the lack of long-term wind observation at the potential sites. There are 221 meteorological stations between SMN and INIFAP recording data during the years 2009 and 2010. In addition to the meteorological stations, 21 points were selected from SMSEN for evaluation because they provide good geographical coverage of the high wind potential areas, as shown in Fig. 1. The wind speeds were measured using anemometers at fixed positions of different heights, and the continuously recorded wind data were recorded every 10 minutes. For each selected site, we extracted a complete two-year data record. Accurate estimation of the wind speed distribution is critical to the assessment of the wind energy potential, the site selection of wind farms, and the operations management of wind power conversion systems [60].

3.2. Wind Power Density (WPD)

Generally, two methods exist to evaluate wind power. The first and the most accurate method to calculate the wind power potential is based on the measured values that are recorded at meteorological stations [61]. Wind Power Density (WPD), P in Eq. 2, is a useful means to evaluate wind resources available at a potential site. The WPD, measured in W/m^2, indicates how much energy is available at the site [62]. WPD is a nonlinear function of the Probability Density Function (PDF) of the wind speed and air density. WPD is proportional to the cube of the wind speed and can be calculated using the following equation:

$$P = \frac{1}{2} d v^3 \left[W/m^2\right] \tag{2}$$

where d is the air density, which, for standard conditions (e.g., at sea level, with a temperature of 15 °C and a pressure of 1 atmosphere), is equal to 1.225 kg/m^3, and v is the wind speed (m/s). The average wind power density for any specified period of time can be calculated as follows:

$$\overline{P} = \frac{1}{2n} d \sum_{i=1}^{n} v^3 = \frac{1}{2} d v^3 \left[W/m^2\right] \tag{3}$$

where n is the number of all of the data that was used in the specified period of time.

The second method to assess the wind power potential is using a PDF [63]. Among several probability distribution

functions that have been presented, the Weibull PDF is most commonly used [64]. The statistical analysis of the measured data covered the wind speed and direction, the mean wind speed and power density, and the Weibull distribution parameters of k and c, *i.e.*, the shape factor and scale factor, respectively. The shape factor will typically range from 1 to 4. For a given average wind speed, a lower shape factor indicates a relatively wide distribution of wind speeds around the average, while a higher shape factor indicates a relatively narrow distribution of wind speeds around the average. A lower shape factor will normally lead to a higher energy production for a given average wind speed [64].

Eq. 4 can be used to obtain the mean wind speed

$$\bar{v} = \int_0^\infty v f(v) dv \tag{4}$$

On the basis of the determined standard deviation of the wind speed, an analysis is performed of the wind turbulence at the measurement site. Based on the method of the sum of least squares, a mathematical method for the estimation of the vertical wind speed profile was developed.

The Weibull distribution function for wind speed is characterised by two parameters: one for the shape (k) and the other for the scale (c); the probability function is shown in Eq. 5.

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \tag{5}$$

where v is the wind speed (m/s), k is the shape factor (dimensionless), and c is the scale factor (m/s). The cumulative density function is

$$F(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^k\right). \tag{6}$$

Eqs. 5 and 6 can be substituted into Eq. 4 as follows

$$\bar{v} = \int_0^\infty v \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) dv. \tag{7}$$

To solve Eq. 7, let v/c = v*, and

$$\bar{v} = kc \int_0^\infty (v*)^k \exp\left(-v*^k\right) dv* \tag{8}$$

and let $(v*)^k$ = t. Then, Eq. 8 becomes

$$\bar{v} = c \int_0^\infty t^{1/k} e^{-t} dt \tag{9}$$

$\Gamma(z)$ is the gamma function and is defined as follows:

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt \tag{10}$$

The Weibull factors can be obtained as follows:

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{11}$$

$$c = \frac{\bar{v}}{\Gamma(1+1/k)} \tag{12}$$

where $\bar{v}$ and σ are the mean wind speed and its standard deviation, respectively, for any specified periods of time.

Comparing the exponents of ***t*** in the Eqs. 9 and 10 gives (z - 1) = 1/k, or z = (1 + 1/k).

Therefore, another form to calculate the mean wind speed using the Weibull methodology is

$$\bar{v} = c\Gamma(z) = c\Gamma(1+1/k) \tag{13}$$

The standard deviation of the Weibull function can be shown to be

$$\sigma = c\left[\Gamma(1+2/k) - \Gamma^2(1+1/k)\right] \tag{14}$$

Table 4
Values of some of the Weibull shape parameters.

k	$\Gamma(1+1/k) = \bar{v}/c$	$\Gamma^2(1+1/k)$
1.25	0.931840	0.914978
1.5	0.902745	0.857724
1.6	0.896574	0.839727
1.7	0.892244	0.823802
1.8	0.889287	0.809609
1.9	0.887363	0.796880
2.0	0.886227	0.785398
2.1	0.885694	0.774989
2.2	0.885625	0.765507
2.3	0.885915	0.756825
2.4	0.886482	0.748873
2.5	0.887264	0.741535
3.0	0.892979	0.712073
3.5	0.899747	0.690910
4.0	0.906402	0.674970

The solution of the gamma function may be found in mathematical tables or symbolic programs [65]. Table 4 lists the values of the gamma function for k equal to 1.25 through 4.

Table 5 shows the statistics of the wind speed and the Weibull parameters obtained from the database source. Table 5 presents the wind speed statistical data of all of the meteorological stations considered in this study; the mean wind speed of all of the studied area is 4.99 m/s, and the maximum and minimum wind speeds are 13.91 m/s and 0.01 m/s, respectively. The Weibull parameters can be used to assess wind resource in the studied area: shape parameter 1 < ***k*** < 2 was present in the data of 204 meteorological stations and ***k*** > 2 in the data of 34 meteorological stations. In all cases, the scale parameter ***c*** was approximately the mean wind speed at each point.

After establishing the parameters ***c*** and ***k*** that describe the Weibull function and therefore the behaviour in terms of wind speed, the wind potential was determined from the studied area by calculating the wind power available multiplied by the number of hours included in the study.

The Weibull function charts, one per state, are presented in Fig. 2. As shown in Fig. 2, the Weibull distribution of five meteorological stations (one per state) provides the k factor for each station; in general, these values of the k factor indicate that the wind speed has variations in these places.

To identify the monthly variation of the WPD, Fig. 3 shows the WPD of each state considered. The figure indicates that northern Mexico has good wind power density, with the region with the highest WPD being the state of Tamaulipas, where the WPD in some months (September and October) is higher than 800 W/m^2. Nuevo Leon is the state with the second highest WPD, which was at an acceptable level, with June exhibiting a WPD of over 500 W/m^2.

The WPD characteristics are illustrated in the next 13 maps, with one per month and an annual map. A GIS (ArcGIS) was applied to prepare the maps with reference to the WPD at a height of 50 m.

Figs. 4–16 show the WPD of Northern Mexico, with the months exhibiting a good WPD being April, May, June, July and August, with WPD values of 622 W/m^2, 628 W/m^2, 661 W/m^2, 690 W/m^2 and 860 W/m^2, respectively. The highest WPD of 1000 W/m^2 occurs in September and October. From Fig. 16, the annual WPD of northern Mexico indicates that the highest WPD is between 142 W/m^2 and 294 W/m^2 and occurs at a small region in the Northwest of Sonora, north of Chihuahua, and the central region of Tamaulipas.

3.3. Power Output and Useful Hours

To calculate the net power and energy output, it is necessary to calculate the gross power output, which depends on four factors: the turbine's power curve, the wind speed at the hub height, the air

Table 5
Wind speed statistical data.

Point/Station	Wind Speed (m/s)			Weibull	
	mean	max	min	*k*	*c* (m/s)
Point_1	5.63	8.93	0.97	1.17	5.14
Point_2	4.79	7.56	0.19	1.49	4.68
Point_3	8.94	13.77	0.14	1.66	8.80
Point_4	3.91	7.32	0.09	1.78	3.87
Point_5	4.64	9.75	0.15	1.44	4.59
Point_6	8.17	12.86	0.76	1.36	8.12
Point_7	4.49	8.15	0.33	1.10	4.43
Point_8	3.38	8.63	0.28	2.67	3.95
Point_9	3.85	8.79	0.77	1.95	3.72
Point_10	3.91	9.64	0.89	1.97	3.86
Point_11	6.74	10.66	0.51	1.20	6.71
Point_12	5.19	9.79	0.89	1.39	5.28
Point_13	3.16	8.61	0.65	1.56	3.21
Point_14	4.03	7.63	0.24	1.93	4.17
Point_15	4.30	8.08	0.7	1.89	4.59
Point_16	5.22	9.34	0.43	1.90	5.33
Point_17	6.78	10.54	0.38	1.37	6.75
Point_18	4.58	9.51	0.56	1.76	4.32
Point_19	6.23	11.61	0.9	1.28	6.18
Point_20	5.48	10.29	0.76	1.67	5.43
Point_21	3.44	8.90	0.74	1.49	3.23
Chinipas	4.21	7.72	0.20	1.28	4.92
Guachochi	4.12	8.66	0.62	1.72	4.89
Urique	3.77	4.20	0.50	1.20	3.98
Maguarichi	4.72	7.08	0.69	1.68	4.62
Chinatú	4.47	8.59	0.92	1.55	4.89
Basaseachi	4.28	8.28	0.06	1.62	4.11
Ciudad Delicias	4.52	8.42	0.47	1.72	4.03
Jimenez	4.92	9.64	0.04	1.45	4.41
Cd. Cuauhtemoc	4.60	9.72	0.66	1.60	4.09
Ojinaga	4.58	9.54	0.55	1.28	4.22
Villa Ahumada	5.45	9.99	0.90	1.87	5.95
El Vergel	4.02	11.61	0.45	1.63	4.88
Nueva Rosita	5.68	10.64	0.44	1.79	5.81
Santa Cecilia	5.42	9.24	0.98	1.30	5.10
Cuatro Cienegas	4.35	10.14	0.32	1.82	4.88
Venustiano Carranza	4.35	9.81	0.18	1.15	4.94
Morelos – Muzquiz	5.03	11.09	0.38	1.17	5.71
Presa El Cuchillo	5.89	12.71	0.79	1.12	5.18
Nogales	5.19	10.05	0.74	1.06	5.87
Alamos	6.69	11.42	0.01	1.63	6.93
Yecora	4.99	9.86	0.70	1.78	4.14
Hllo - Bahia de Kino	4.32	9.17	0.16	1.68	4.16
Caborca	5.69	9.79	0.23	1.48	5.29
Sonoyta	4.38	8.18	0.53	1.61	4.78
San Luis Rio Colorado	4.73	11.80	0.43	1.70	4.10
Matamoros	5.90	10.79	0.23	1.89	5.36
San Fernando	4.21	9.85	0.13	1.72	4.67
Ciudad Mante	4.62	10.99	0.74	1.80	4.16
Villagran	4.28	13.58	0.91	1.20	4.88
Jaumave	5.90	10.89	0.88	1.69	5.06
Barra del Tordo	4.04	12.34	0.83	1.83	4.88
La Cuesta	6.96	9.45	0.29	1.89	6.16
La Florida	6.99	10.07	0.50	1.35	6.50
Guadalupe	5.14	10.01	0.02	1.18	5.84
Campo 52	4.76	13.66	0.15	1.76	4.19
El Norteno	4.43	12.28	0.09	1.89	4.27
El Chalate	4.67	13.00	0.57	1.71	4.06
Agroindustrial Sonora	3.99	9.26	0.08	1.84	3.23
Don Enrique	5.87	8.23	0.24	1.38	5.49
Santa Ines	6.31	8.21	0.88	1.11	6.14
Perico 2	4.86	13.91	0.52	1.23	4.17
La Perseverancia	5.85	11.39	0.91	1.49	5.34
Hercules	5.28	10.47	0.88	1.41	5.07
CECH-INIFAP	4.99	12.89	0.33	1.84	4.50
El Bervano	3.68	7.48	0.18	1.43	3.22
Perico I	4.08	9.19	0.48	1.24	4.29
El Compa	4.23	11.25	0.66	1.33	4.89
El Rosario	5.50	9.09	0.32	1.74	5.13
San Carlos	5.07	11.45	0.32	1.16	5.74
Seawaterfarm	4.81	9.71	0.16	1.84	4.20
Block-727, SI	5.38	11.06	0.16	1.75	5.52
Block 111	4.55	10.08	0.33	1.24	4.04

Table 5 (*continued*)

Point/Station	Wind Speed (m/s)			Weibull	
	mean	max	min	*k*	*c* (m/s)
Predio El Jazmin	4.39	9.21	0.93	1.63	4.76
Block-609	5.79	11.84	0.67	1.75	5.28
Block-414	5.26	10.87	0.43	1.19	5.80
CIANO	4.82	9.04	0.05	1.30	4.60
Block-1317, SI	6.04	11.68	0.49	1.93	6.90
Block-1201	5.00	10.05	0.08	1.47	5.12
Block-1418	4.35	9.93	0.25	1.27	4.15
Block-1730	5.63	10.42	0.76	1.60	5.06
Block-2328	5.03	9.86	0.52	1.33	5.45
Tesia	4.18	9.12	0.59	1.64	4.44
Tres Carlos	5.21	10.56	0.58	1.33	6.00
Mumuncuera	6.59	9.08	0.42	1.95	6.02
La Union	4.70	9.94	0.62	1.87	4.49
Jupare	4.27	10.02	0.58	1.23	4.56
San Luis	5.46	9.89	0.84	1.47	5.71
Torocobampo	4.56	9.76	0.30	1.57	4.65
Block-1806	5.85	11.72	0.65	1.43	5.28
Block-2210	4.20	9.03	0.70	1.51	4.74
María Eugenia	5.07	9.39	0.17	1.72	5.75
Canutillo	5.81	10.40	0.48	1.63	5.74
El Delirio	4.70	9.36	0.85	1.37	4.54
La Candelaria	5.72	10.45	0.13	1.49	5.99
Campo Exp Caborca	5.74	9.90	0.66	1.91	5.02
El Rocio	4.34	10.15	0.34	1.00	4.16
San Pablo	4.62	9.79	0.70	1.57	4.10
EL Pedernal	5.10	9.03	0.28	1.64	5.76
San Gabriel	4.22	9.24	0.12	1.96	4.17
Ignacio Palacios	5.33	10.92	0.25	1.24	5.01
Módulo 1	4.16	9.13	0.18	1.11	4.07
Moctezuma	5.03	10.29	0.63	1.55	5.21
CEMAY	4.03	9.13	0.98	1.01	4.79
El Chapote	4.45	9.16	0.56	1.40	4.92
Buaysiacobe	4.06	10.27	0.44	1.55	4.96
Sahuaral	6.21	10.06	0.77	1.04	6.55
Block 2029	5.80	9.25	0.02	1.97	5.18
Rancho Roncesvalles	5.03	9.22	0.05	1.65	5.85
Rancho La Rosita	4.36	9.54	0.22	1.59	4.77
Rancho El Conejo	4.88	9.67	0.63	1.36	4.61
Emiliano Zapata	4.43	9.54	0.45	1.23	4.71
Rancho Guadalupe	4.43	10.16	0.88	1.43	5.25
Rancho La Gloria	5.87	10.39	0.52	1.72	6.18
Rancho El Padrino	4.86	9.56	0.21	1.70	4.24
Empacadora de Melon	4.90	9.03	0.46	1.69	5.67
Parras el Alto	4.09	9.99	0.86	1.70	5.56
El Porvenir	5.01	10.44	0.73	1.67	6.77
Rancho Las Mercedes	5.83	9.30	0.91	1.30	5.92
Campo Ex La Laguna	5.67	9.90	0.68	1.39	6.03
Rancho Los Pirules	4.03	9.06	0.12	1.77	4.77
Rancho PRONATURA	4.06	9.25	0.43	1.85	4.71
Tanque Nuevo	6.24	10.01	0.92	1.49	6.07
Rancho El Cedral	5.64	10.05	0.78	1.12	5.80
Rancho El Paraiso	5.51	9.46	0.90	1.57	5.76
Escuela Tecnica 32	5.79	9.57	0.08	1.24	5.23
Rancho Las Cabras	4.77	10.98	0.65	1.68	4.37
Rancho Santa Maria	4.96	9.07	0.49	1.74	4.11
Union Ganadera Local	4.87	9.64	0.34	1.09	5.12
Rancho Santa Elena	4.63	10.87	0.02	1.53	4.81
Campo Exp. Zaragoza	5.31	11.32	0.04	1.99	5.67
Rancho Pasta 9	4.11	9.84	0.41	1.29	5.42
Rancho Los Lobos	5.98	10.44	0.21	1.90	6.52
Rancho Los Pilares	5.02	11.74	0.82	1.52	5.78
Alicantes	6.16	9.44	0.80	1.68	6.74
Octavio Chavez	4.06	9.99	0.87	1.18	5.20
Huerta El Maguey	4.96	10.24	0.21	1.15	5.11
Rancho El Chueco	4.48	9.23	0.91	1.08	4.28
Rancho El Socorro	5.89	10.01	0.65	1.42	6.08
Campo Experimental	6.17	11.58	0.20	1.82	6.52
Orinda	5.87	9.34	0.20	1.66	6.23
Lomas del Consuelo	4.23	10.87	0.39	1.71	4.90
Lazaro Cardenas	4.13	9.60	0.16	1.83	4.98
Salon de actos	4.16	10.33	0.24	1.56	4.76
El Paraiso	6.41	9.85	0.74	1.44	6.76
El Agronomo	5.02	9.18	0.62	1.35	5.33
Oasis	4.55	9.52	0.46	1.14	5.29

Table 5 (*continued*)

Point/Station	Wind Speed (m/s)			Weibull	
	mean	max	min	*k*	*c* (m/s)
Uniproal	5.99	10.24	0.74	1.94	6.16
Nueva Holanda	4.09	9.86	0.06	1.88	4.66
Los Cienes	4.96	10.51	0.86	1.19	5.28
El Bajio	4.84	9.29	0.10	1.18	5.09
Buena Vista	4.49	9.24	0.83	1.91	4.96
Basuchil	4.15	9.08	0.53	1.45	4.86
Zaragoza	5.09	10.89	0.16	1.82	5.76
Chinacate	4.69	9.72	1.19	2.24	5.03
Loma Verde	4.30	9.84	0.64	1.55	4.81
Maurilio Ortiz	5.10	10.37	1.50	2.15	5.44
Soto Mainez	6.69	11.67	1.38	2.38	6.97
La Tiznadita	5.26	11.40	1.72	2.11	5.94
Sta. Clara	5.31	11.86	1.62	2.21	5.78
Rancho El Barrial	4.77	9.05	0.79	1.83	5.86
Pestañas	5.86	10.11	0.79	1.64	6.24
El Llano	5.60	9.80	1.27	2.64	6.05
Benito	4.44	9.78	1.05	2.09	4.77
Ricardo Flores Magón	4.83	10.75	0.90	1.65	4.02
Quevedo	4.10	9.18	0.86	1.94	4.24
Agricultores Unidos	5.27	11.18	0.81	1.92	5.85
El Valle	4.15	10.81	0.67	1.03	5.00
Barrio Ojinaga	4.99	9.88	0.32	1.98	4.11
Dublan Nuevo	4.94	10.76	0.44	1.07	5.42
Col. El Capulín	4.27	11.53	0.27	1.61	5.53
Samalayuca	6.25	10.96	0.13	1.15	5.79
Praxedis	4.91	9.10	0.35	1.66	5.30
La Sombra	4.00	9.33	0.94	1.48	5.47
Campo 205	4.41	10.19	1.50	2.36	4.80
Buena Vista	5.10	12.63	1.01	2.34	5.95
Ascención	4.43	11.88	1.38	2.10	4.94
Fernández Leal	4.87	10.57	1.53	2.08	4.91
Los Angeles	4.30	10.91	1.44	2.15	4.04
Galeana Reynosa	4.80	9.80	1.23	2.02	5.46
Campo Exp Rio Bravo	4.09	11.85	0.76	1.45	5.58
Los Alhelies	5.24	10.69	0.68	1.45	6.02
Anahuac	4.69	11.63	0.25	1.86	5.15
La Ventana	4.19	10.99	1.95	2.13	5.78
El Avion	5.17	11.13	0.97	1.42	5.45
Martín Rocha	5.03	10.03	0.40	1.90	5.62
San Lorenzo	5.08	10.38	1.01	2.11	5.79
Los Ébanos	4.97	9.38	0.76	1.05	5.29
5 de Mayo	4.45	10.78	0.86	1.08	5.38
Ej. 20 de Noviembre	4.01	8.20	1.04	2.07	4.80
Francisco Villa	5.07	10.59	1.57	2.12	5.91
Ej. Pastores	4.69	9.81	0.96	1.68	5.16
San Fernando	4.77	9.14	0.99	1.20	5.16
Ej. Praxedis	5.24	10.33	0.88	1.11	5.98
Francisco Villa	4.81	10.56	1.14	2.11	5.47
Santa Engracia	5.21	9.11	0.91	1.49	5.71
El Barretal	4.04	10.72	0.88	1.41	4.65
Rancho Katanga	4.43	9.22	0.33	1.84	5.33
Estacion Campo	5.26	10.05	0.18	1.43	6.43
La Jarrita	5.78	10.85	0.48	1.24	5.23
C. E. Aldama	4.20	9.61	0.57	1.73	4.84
La Herradura	5.52	11.96	1.32	2.74	6.06
Satelite	5.95	10.45	0.11	1.36	6.15
Nuevo González	5.84	11.13	0.16	1.84	6.23
CESTAM	4.90	9.83	0.55	1.14	5.09
El Triunfo	5.52	11.71	0.24	1.08	6.14
Cuatro Caminos	5.62	10.36	0.86	1.03	6.96
Estacion Rancho	4.27	10.21	0.29	1.09	4.82
Dr. Arroyo	5.24	9.84	0.43	1.19	5.97
La Aramberri	5.93	11.39	0.41	1.23	6.26
Sandia Aramberri	5.28	10.01	0.62	1.36	5.81
San Jose de Raices	4.77	9.94	0.27	1.20	5.85
Cerro de Agua	5.92	10.00	1.10	2.62	6.26
El Berrendo	5.65	9.72	1.26	2.08	6.13
Altavista	6.59	10.43	1.28	2.12	6.88
El Barreal	4.71	9.64	1.08	2.04	5.06
Casa Blanca	4.74	9.53	1.23	2.20	5.16
Agrodelta El Cuije	5.79	9.28	0.42	1.95	6.08
Ciénega del Toro	5.44	10.90	0.50	1.34	6.86
La Barreta	4.26	9.58	0.59	1.45	4.82
El Naranjo	5.35	11.12	0.84	1.47	5.84

Table 5 (*continued*)

Point/Station	Wind Speed (m/s)			Weibull	
	mean	max	min	*k*	*c* (m/s)
INIFAP General	4.91	9.71	1.30	2.57	5.16
Chihuahuita	4.87	10.14	1.31	2.10	5.24
Rancho Maria	4.13	11.31	0.98	1.53	4.78
Allende	4.75	8.96	0.59	1.27	5.84
Rancho El Popote	5.63	9.90	0.37	1.88	6.19
La Leona	4.99	9.91	0.78	1.11	5.79
San Rafael	5.03	8.13	1.72	2.05	5.86
Laguna de Sanchez	6.10	11.01	0.34	1.55	6.52
Lab. Biotecnologia	5.59	11.82	0.84	1.04	6.13
Vivero El Llano	5.20	10.44	1.00	2.12	5.73
San Isidro	5.45	11.01	1.28	2.07	6.27
Facultad de Agronomia	4.53	9.65	1.12	2.06	5.16
Cerralvo	4.39	9.01	0.75	1.38	4.72
Las Milpillas	5.04	10.62	1.18	2.10	5.93
Sabinas Hidalgo	4.04	9.11	0.37	1.30	4.26
CRFGV-UANL	4.72	9.56	0.98	1.10	5.25
Bustamante	5.55	10.64	0.63	1.58	6.43
Anahuac	4.74	9.38	0.99	1.49	5.15
Aduana	4.78	8.27	1.77	2.04	5.07
San Gabriel	4.68	9.70	1.02	2.18	5.20

density and the blade swept area [65]. To calculate the gross power output in a particular time step, first, the appropriate power curve must be chosen; usually, the power curve whose corresponding air density is closest to the air density in the current time is chosen. For a controlled wind turbine, first, the power output predicted by the power curve for the measured wind speed is calculated. Then, the power output is adjusted according to the following equation:

$$P_W = P_{W0}\frac{d}{d_0} \tag{15}$$

where P_{W0} is the power output predicted by the power curve for the wind speed in the current time step (kW), d is the actual air density in the current time step (kg/m³), and d_0 is the air density at which the power curve applies (kg/m³).

For a pitch-controlled wind turbine, first, the 'effective wind speed' resulting from the current air density is calculated, and then the power curve is used to determine the power output predicted at that effective wind speed. The following equation provides the effective wind speed:

$$U_{eff} = U\left(\frac{d}{d_0}\right)^{1/3} \tag{16}$$

where U is the actual wind speed recorded in the current time step [m/s], d is the actual air density in the current time step (kg/m³), and d_0 is the air density at which the power curve applies (kg/m³).

To estimate the energy output of a wind turbine in the measured wind regime, the following four-step process is performed:

Estimate the wind speed at the hub height of the wind turbine in each time step; use the hub height wind speed and air density in each time step to estimate the gross power output of the wind turbine in each time step; determine the overall mean and the mean in each month of the gross power output and multiply this by the overall loss factor to calculate the mean net power output for each month and for the entire data set; then, multiply the mean net power output by the number of hours in a year (8,760) to determine the annual mean net energy production, and similarly, multiply the monthly mean net power output by the number of hours in each month to find the monthly mean net energy production [66].

Eq. 15 is typically used to calculate mean net power output.

$$\overline{P}_{net} = (1 - f_{overall})\overline{P}_{gross} \tag{15'}$$

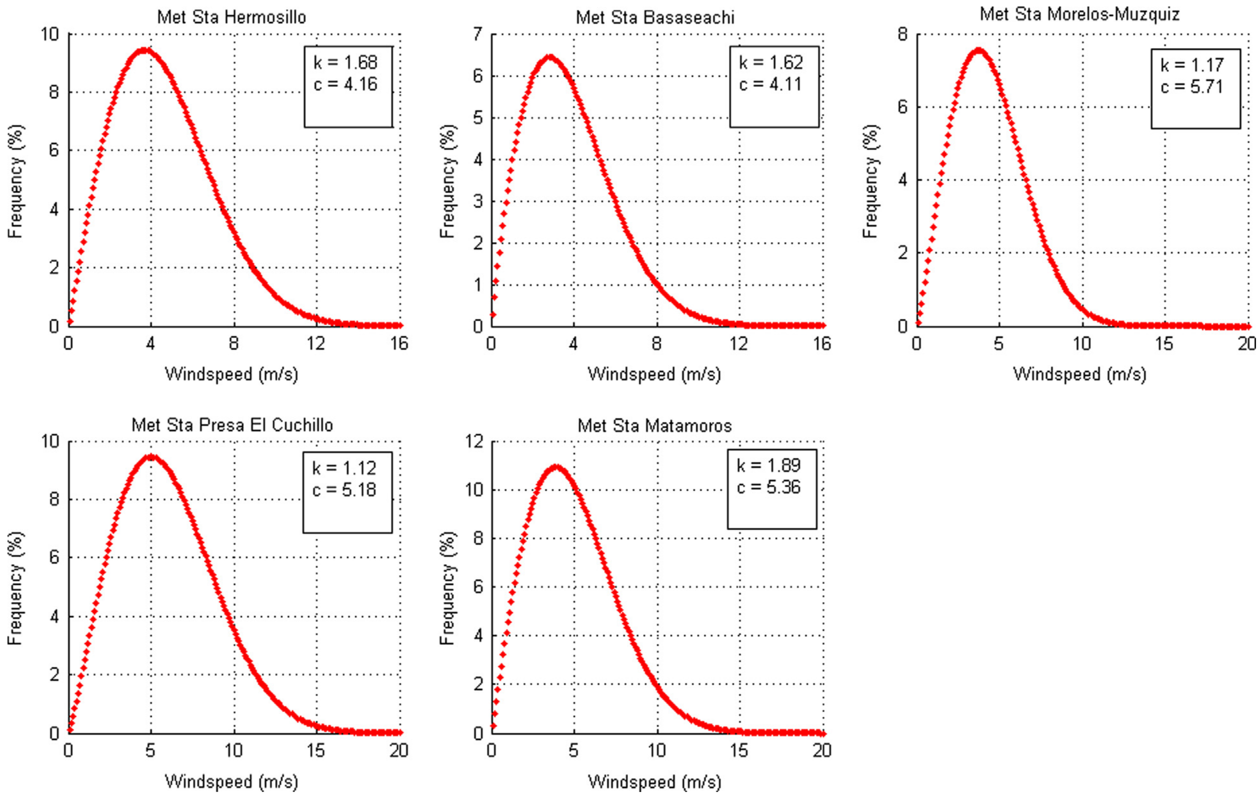

Fig. 2. Weibull distribution of five meteorological stations.

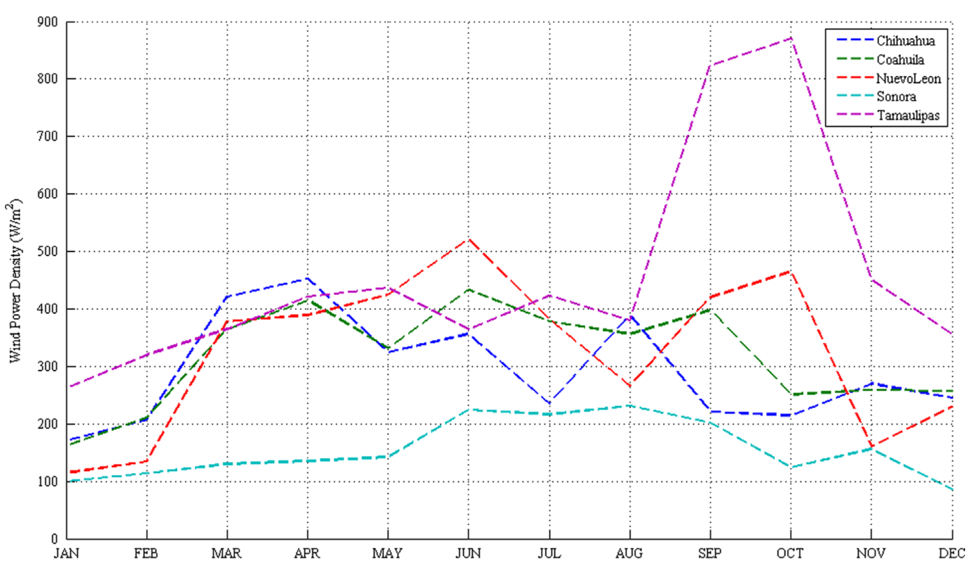

Fig. 3. Variation in WPD by state.

where $\overline{P}_{gross}$ is the mean gross power output before losses (kW), and $f_{overall}$ is the overall loss factor.

The net power output (kW) that could be generated was calculated by modelling data produced using an ACCIONA AW 77/1500 Class II wind turbine, which is commonly used in Mexico [67].

Calculate the number of useful hours necessary to assess wind speed. At a 3 m/s wind speed, the WTG starts to generate power. The WTG produces power up to the cut-out wind speed. The duration of the wind speed from 3 m/s to the cut-out wind speed will be the useful hours for energy production. In this way, we calculated how many hours during the day exhibit a wind speed above 3 m/s and below the cut-out wind speed, according to [21]. Fig. 17 shows five examples of power output (kW), useful hours (hrs) and wind speed

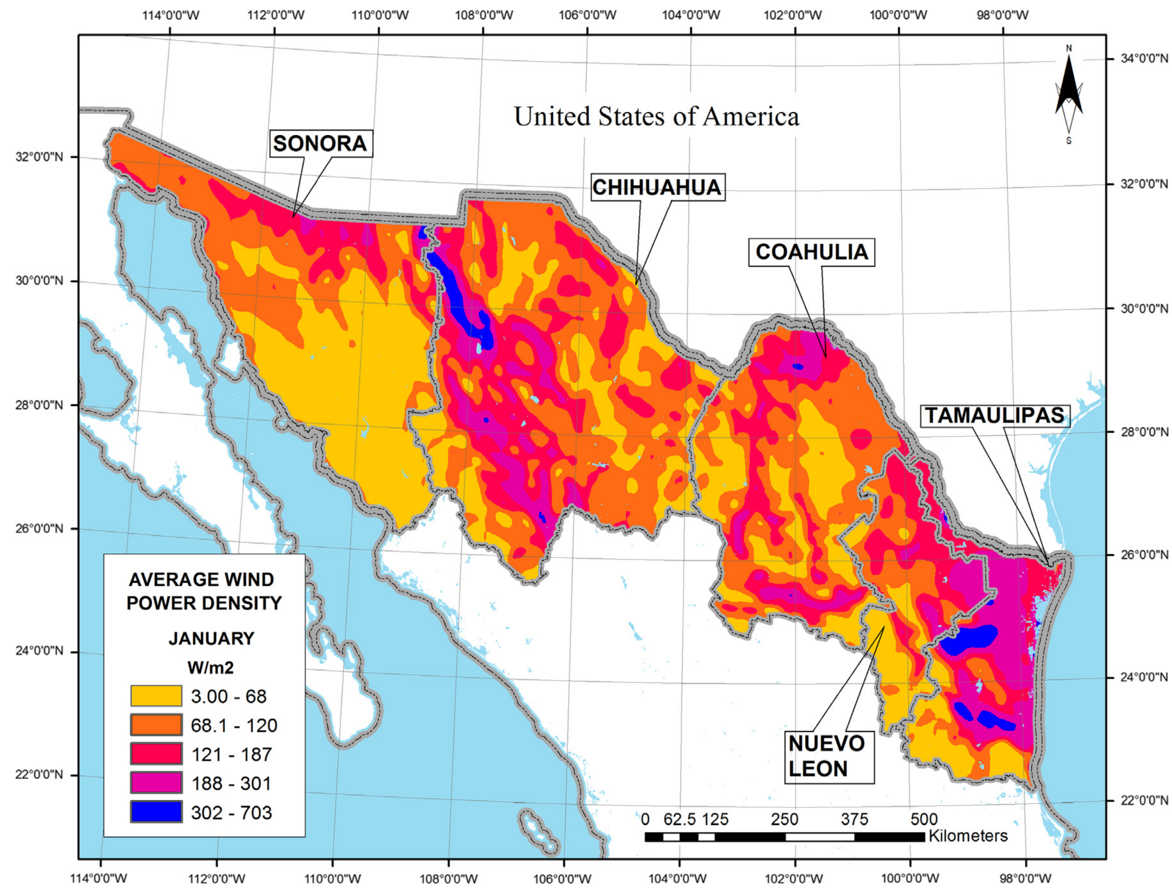

Fig. 4. Northern Mexico WPD of January.

(m/s) from five meteorological stations, one per state, in the north of Mexico.

The state of Sonora exhibits a mean wind speed of approximately 8 m/s, with a mean net power output of 4×10^4 kW and 4 hrs as the mean useful hours of exploitable wind speed per day. The state of Chihuahua has a mean net power output of 1.2×10^5 kW, which is due to a mean wind speed of 8 m/s and 10 hrs of mean useful hours per day. Coahuila has a mean net power output of 3×10^4 kW and a mean wind speed and useful hours per day of 3.5 m/s and 5 hrs, respectively. Nuevo Leon has a mean net power output of 1.4×10^5 kW, a mean wind speed of 6 m/s and mean useful hours of 8 hrs. The state of Tamaulipas has a mean net power output of 2×10^4 kW, a mean wind speed of 4 m/s and 6 hrs of mean useful hours.

3.4. Daily pattern

To characterise the average day or daily pattern for each station, the method of [27] was used. The results are presented in five examples, one per state, in Fig. 18. Fig. 18 shows the wind speed behaviour during the day; in all cases, the wind speed decreases from the first hours of the day and begins to rise in the afternoon. This behaviour can be very interesting to combine with solar energy [68], as was considered by Qin-Yi et al. [69], who combined a hybrid wind-solar system to a rooftop wind-solar hybrid heat pump system. In the case of northern Mexico, the solar resource could be found to have its best potential in the middle of the day and the wind resource has its best potential during the rest of the day.

3.5. Mapping Wind Speed in northern Mexico

The kriging estimators [70] belong to the class of the best linear unbiased estimators (BLUE). The kriging estimators are minimum variance estimators and yield, within the class of the linear estimators, "optimal" statistical performances.

Two of the most used kriging models are the ordinary kriging (OK) and the universal kriging (UK). The first is based on the hypothesis of a constant mean of the sampled data. However, this requisite is not held by many fields. For those fields that have a spatial trend of their mean value, the UK (also called kriging under trend constraints) is used [71]. The basis of the hypothesis of the UK is that it is possible to write the trend function as a linear combination of elementary functions, which are generally monomial. The weights of this combination are called drift coefficients. Whatever elementary functions are chosen, a constant term f_0, representing the mean value of the trend, must always be present. In practice, the OK, with the optimisation of the estimate of a punctual value of the field, also optimises the mean value of the same field; the UK yields estimates with the minimum overall variance of the combined estimate of the trend function and of the small scale variability.

Data were interpolated using the Kriging method from ArcGIS v10; the Kriging method assumes that the distance or direction between the sample points reflects a spatial correlation; the Kriging method fits a mathematical function to a specified number of points, as shown in Eq. 10. GIS was applied to prepare various thematic maps with reference to the wind resource and the wind power density at a height of 80 m. Figs. 19 to 30 show the average wind resource map of each

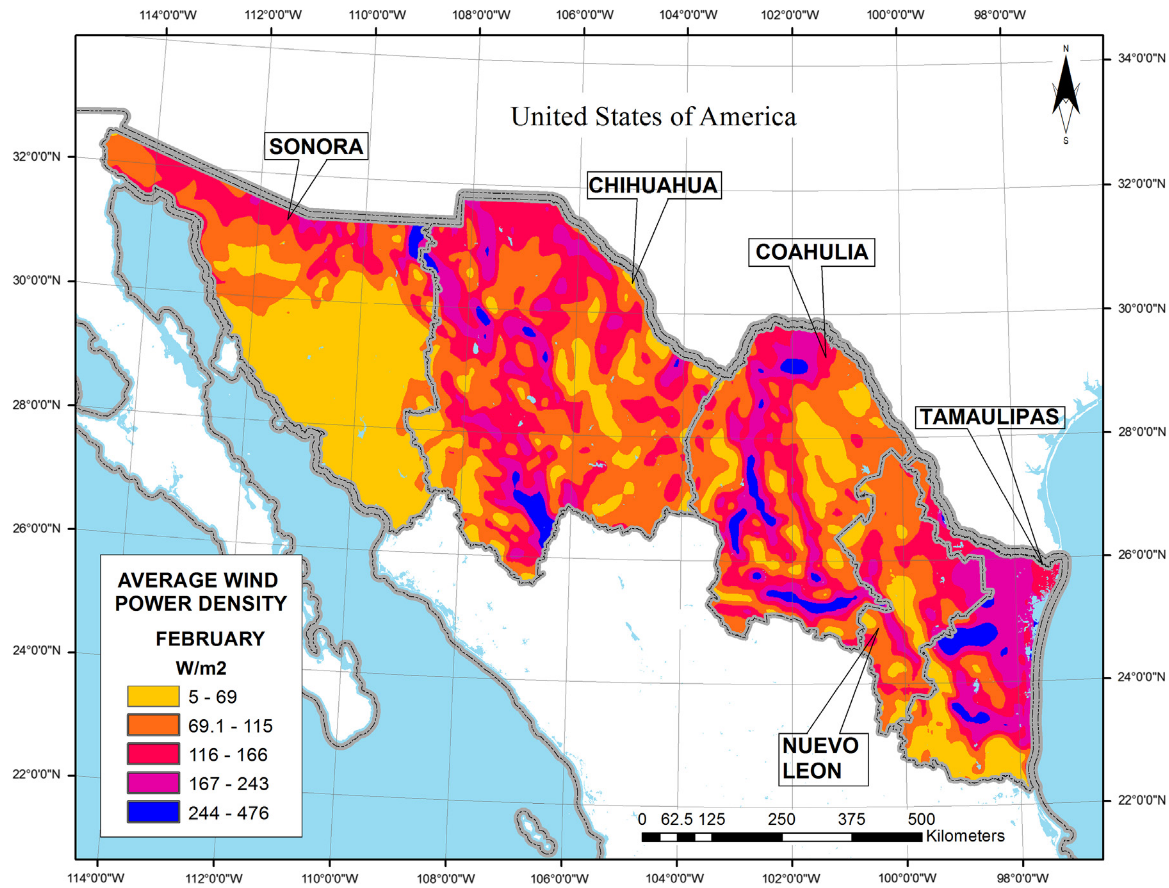

Fig. 5. Northern Mexico WPD of February.

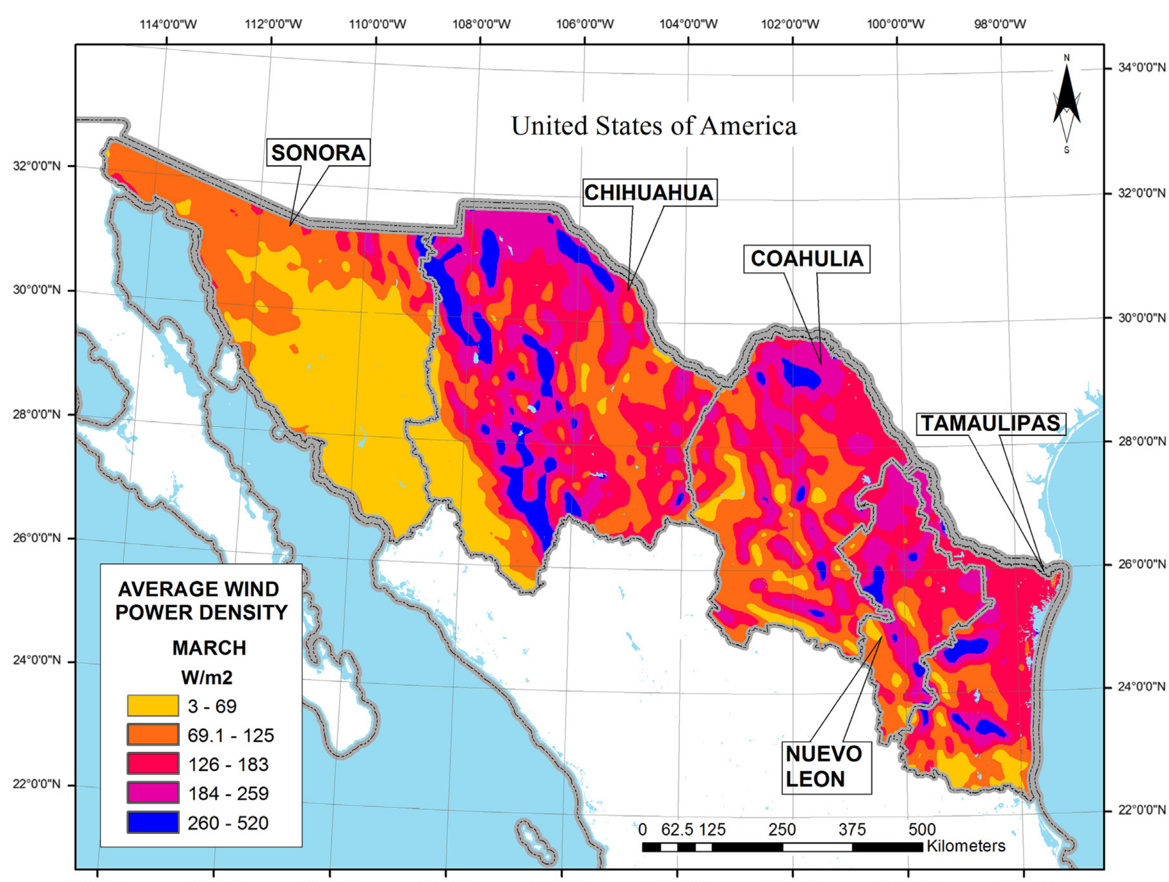

Fig. 6. Northern Mexico WPD of March.

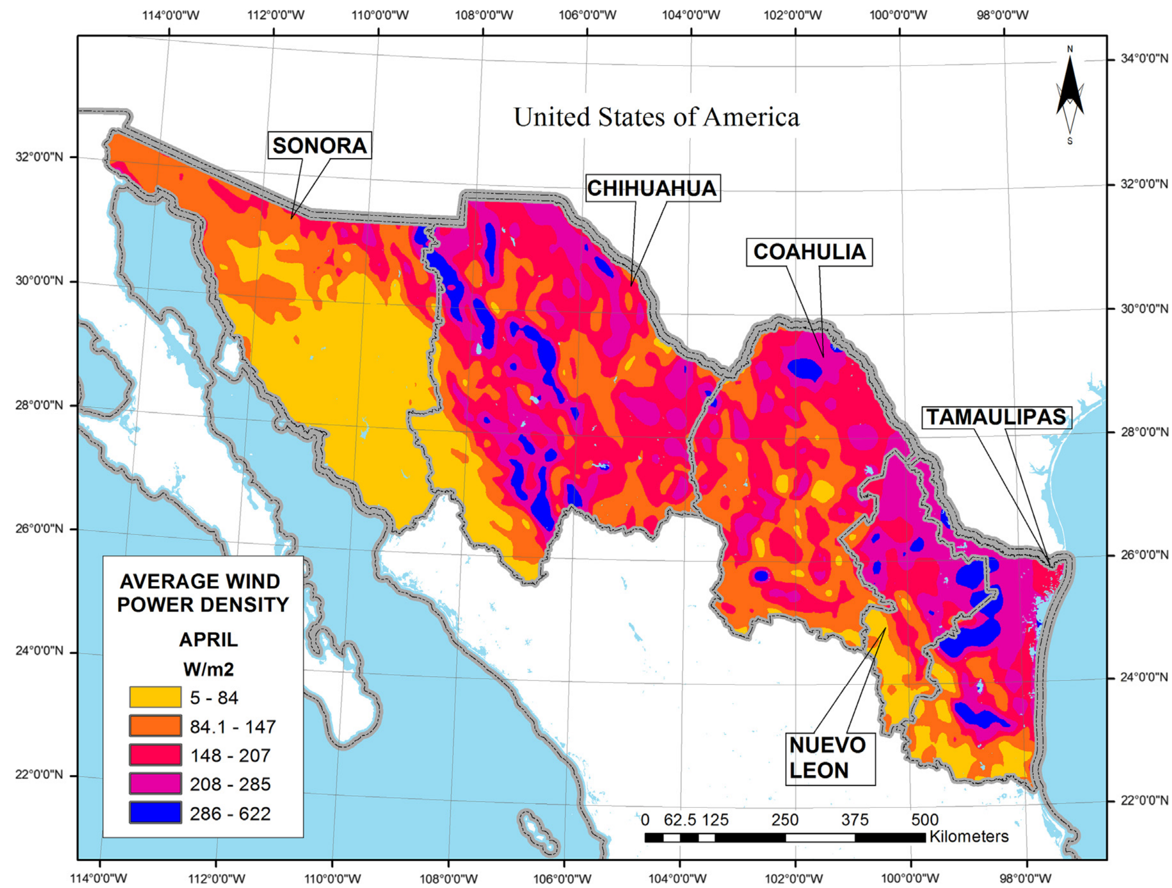

Fig. 7. Northern Mexico WPD of April.

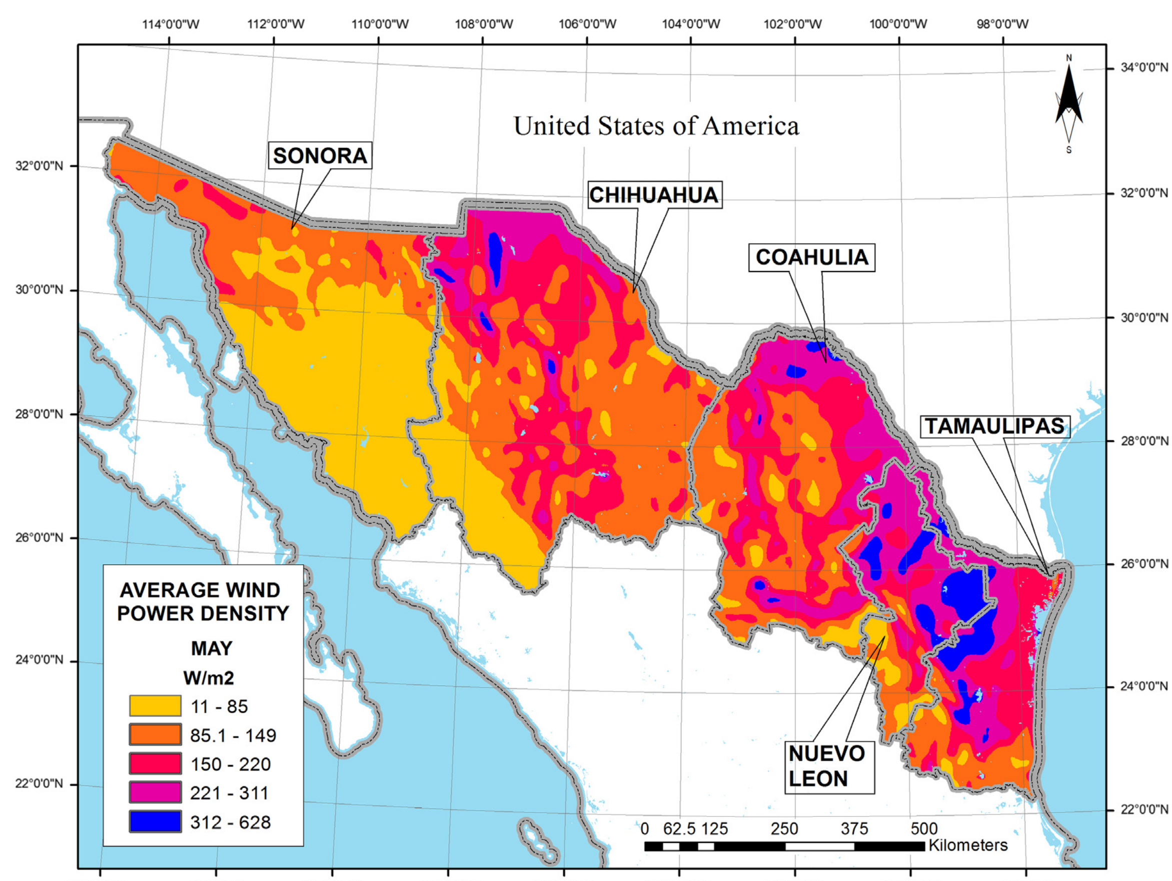

Fig. 8. Northern Mexico WPD of May.

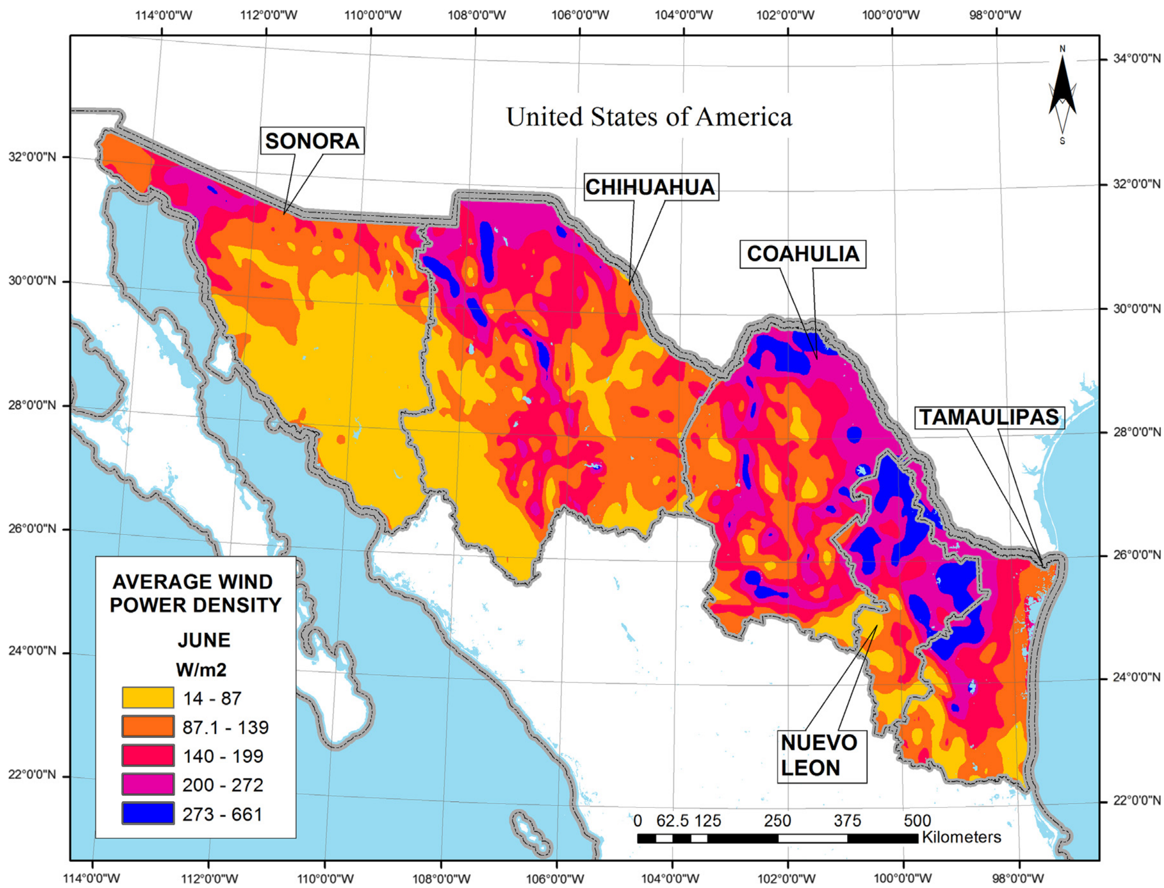

Fig. 9. Northern Mexico WPD of June.

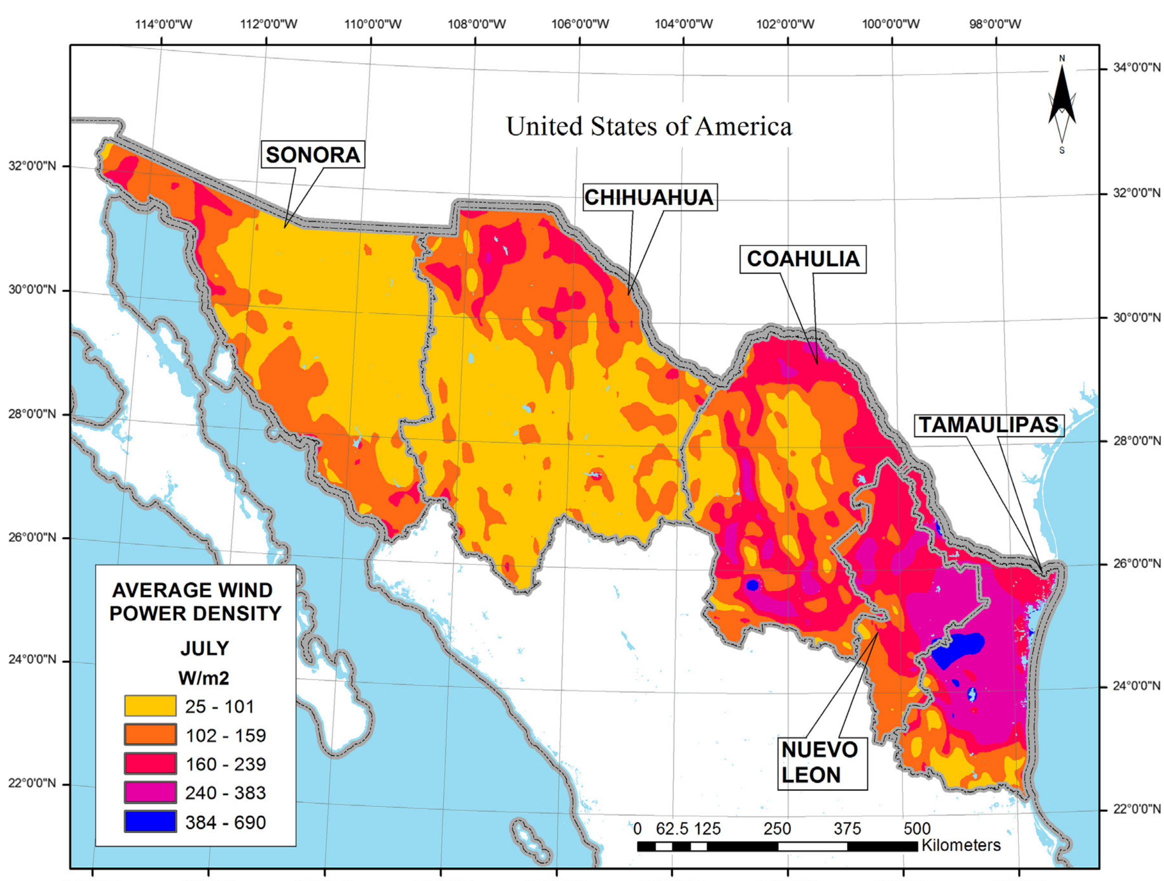

Fig. 10. Northern Mexico WPD of July.

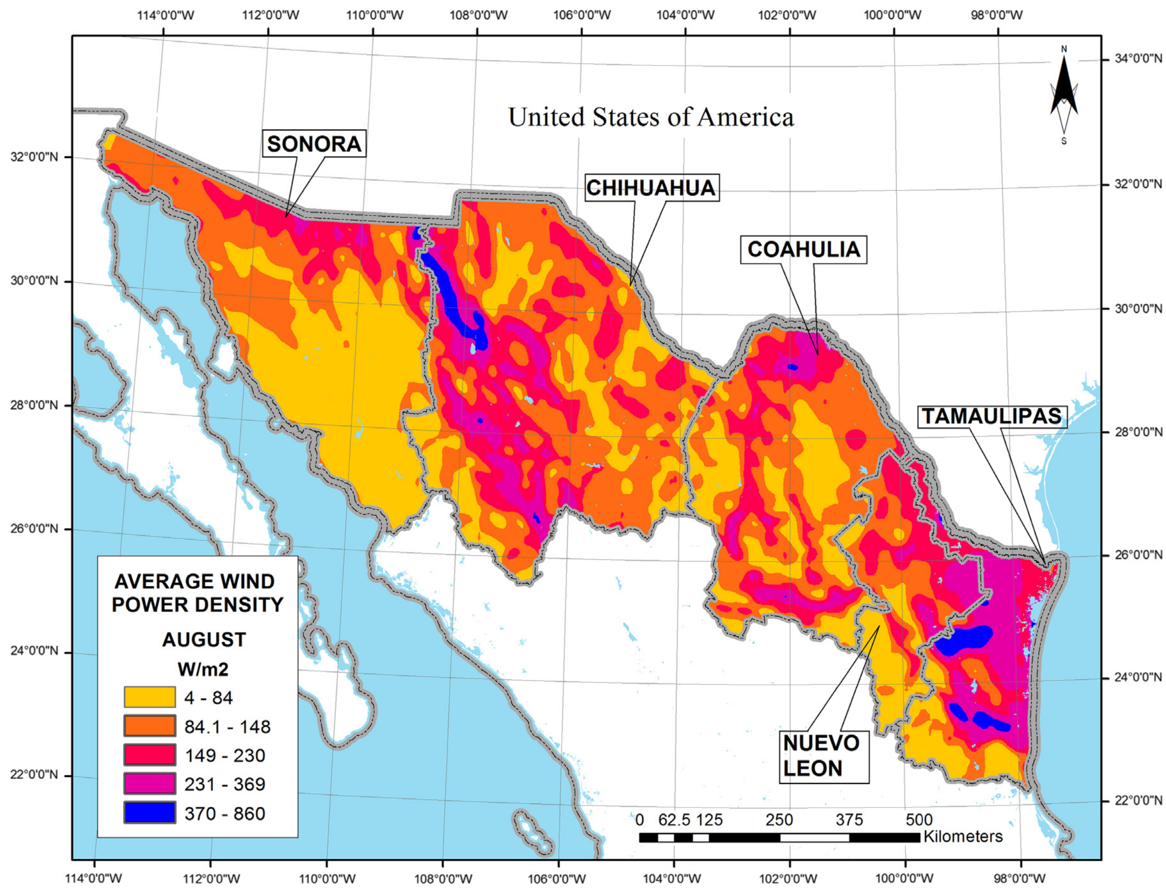

Fig. 11. Northern Mexico WPD of August.

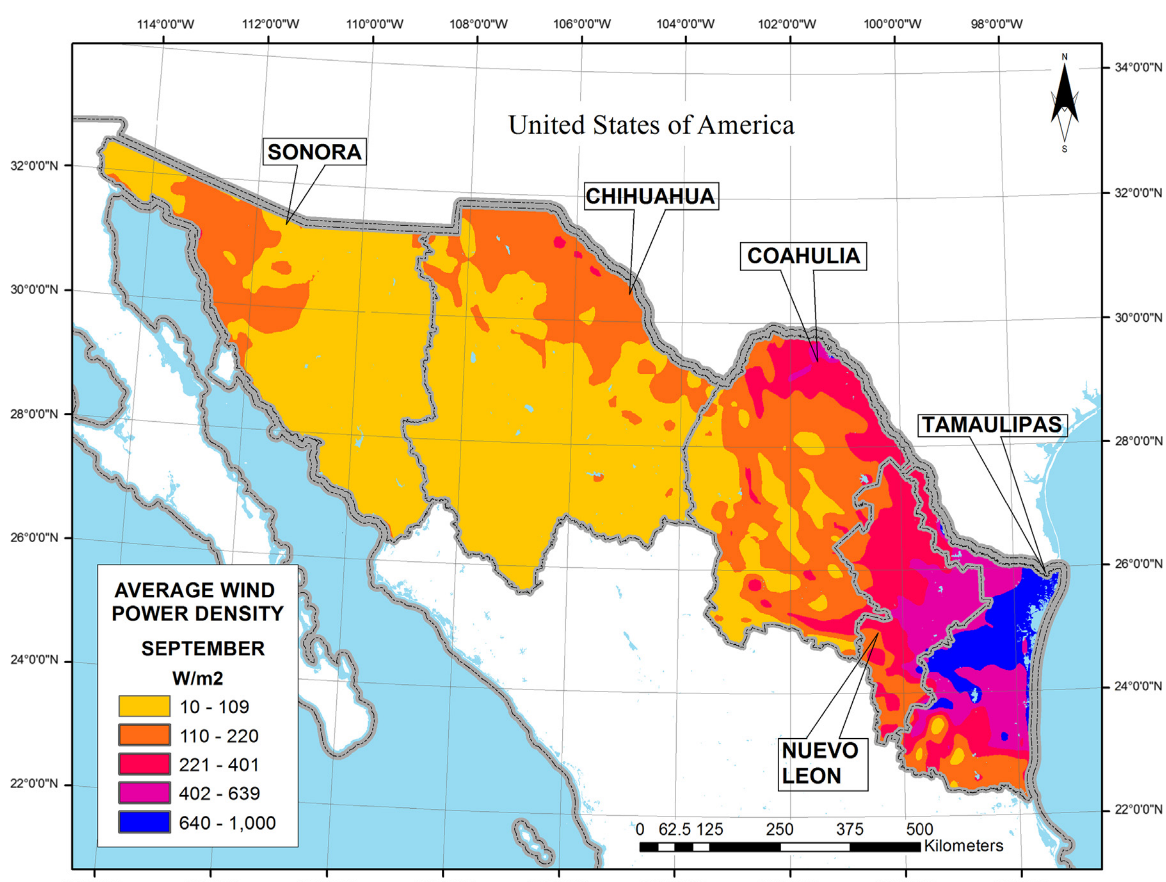

Fig. 12. Northern Mexico WPD of September.

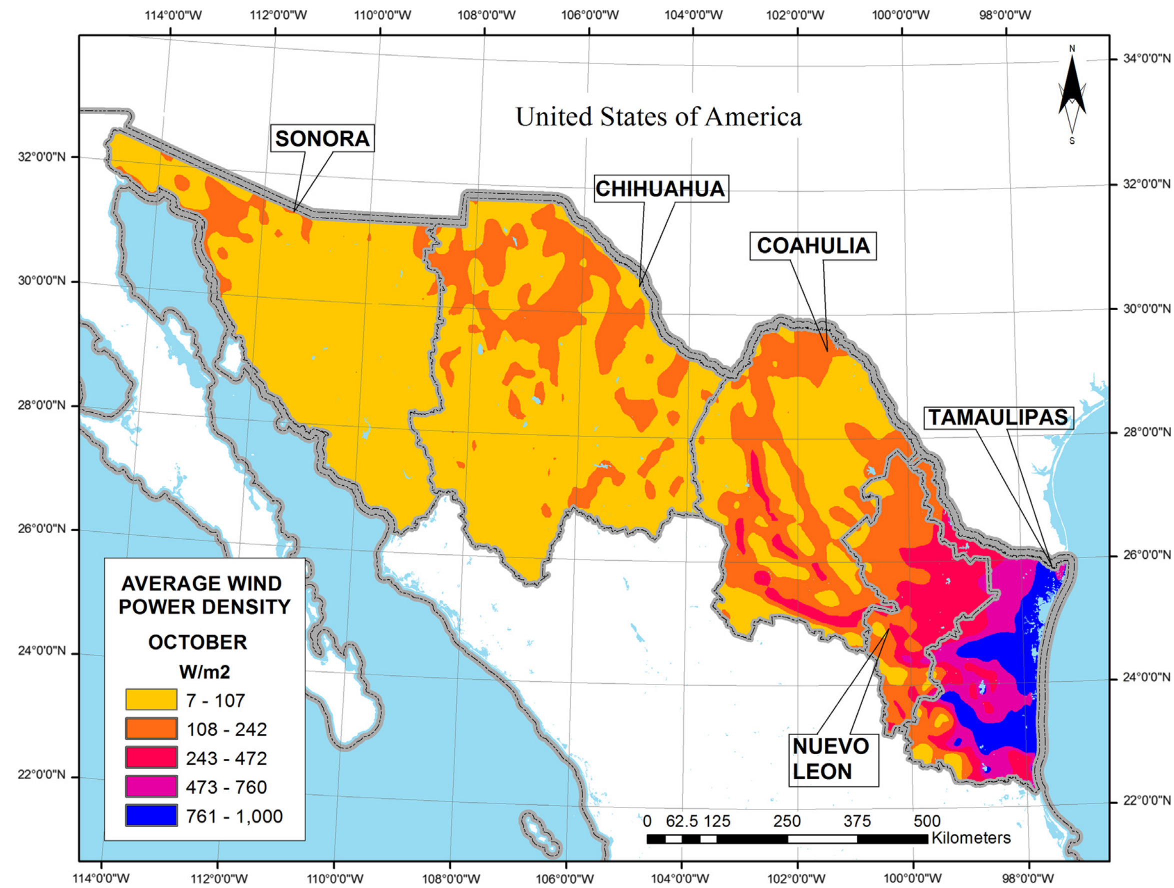

Fig. 13. Northern Mexico WPD of October.

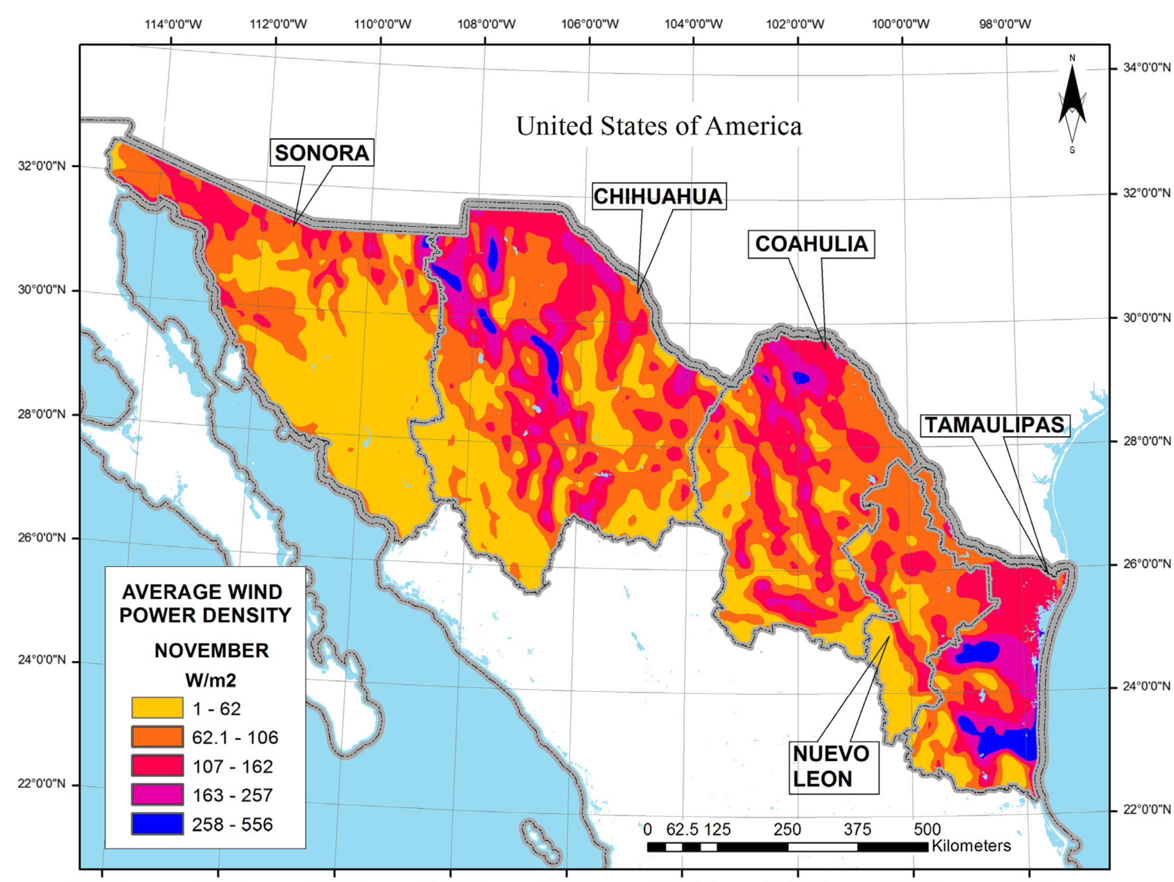

Fig. 14. Northern Mexico WPD of November.

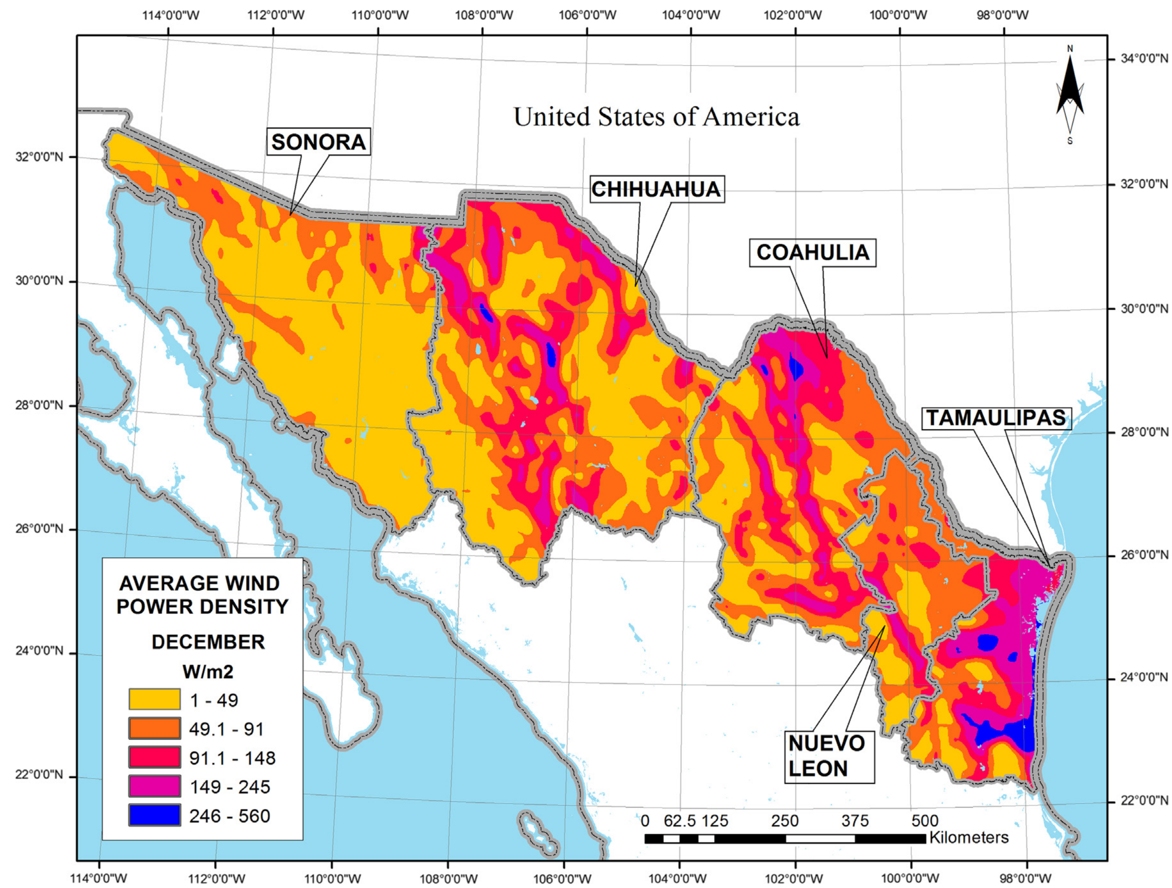

Fig. 15. Northern Mexico WPD of December.

month of 2010.

$$\hat{Z}(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i) \quad (16)$$

where $Z(S_i)$ is the measured value at the ith location, λ_i is an unknown weight for the measured value at the ith location, S_0 is the prediction location, and N is the number of measured values.

February has, in most parts of northern Mexico, a good wind resource, as shown in Fig. 20; Chihuahua (the largest Mexican state) exhibits a wind speed above 6.81 m/s at the mountain zone, but almost its entire territory has wind speed of 4.01 m/s, which is very interesting because the wind useful hours start for wind speeds above 3 m/s. The northern states in July have some areas with good wind resource, as shown in Fig. 24; Coahuila and Tamaulipas states have wind speeds above 6.81 m/s, and the state with less wind resource in July is Sonora.

November exhibits a high level of wind resource in almost the entire territory considered, as shown in Fig. 29; the map allows the identification of good wind resource zones. Chihuahua, Coahuila and Tamaulipas have regions above 6.81 m/s of wind speed. Sonora has a wind speed above 3.01 m/s only in the north.

Fig. 31 shows the annual average wind speed at northern Mexico.

As shown in Fig. 31, the average wind speed during the entire year at northern Mexico is above 4.51 m/s in four states, except for Sonora, where only at its north is the wind speed above 4.51 m/s. With these data, it is possible to work on planning the geographical location of wind farms in the northern states of Mexico.

4. Conclusions

Among the renewable energy options, wind power has been identified as an alternative for future energy demands in northern Mexico. The installed wind power is still far below the potential estimates, both for all of Mexico and in a regional context, e.g., no wind farm exists in northern Mexico. However, the wind power density in northern Mexico is interesting because it has some areas with good wind power density. The state of Tamaulipas has the highest wind power density calculated, but the north of Nuevo Leon has, in a large part of its territory, a wind power density of over 230 W/m^2. The relative amounts of wind power that can be generated from each of the five northern states considered are Sonora 11.43%, Chihuahua 34.29%, Coahuila 8.57%, Nuevo Leon 40% and Tamaulipas 5.71%. The five figures were obtained based on the daily pattern of the wind speed, one per state studied. The wind speed determined, in most cases, was found to behave in a similar manner, i.e., the increase in wind speed starts from 4 pm until 6 am the next day. Northern Mexico has some zones with excellent wind speed, e.g., in the states of Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, nearly all of their territories exhibit a wind speed of over 4.51 m/s. This study highlights the great potential of wind energy in the northern states of Mexico, where specific areas could be considered for the installation of wind farms.

The use of renewable energy in Mexico has been growing slowly, with renewable energy use accounting for only 3% of the total national energy generation. Currently, Mexico lacks a

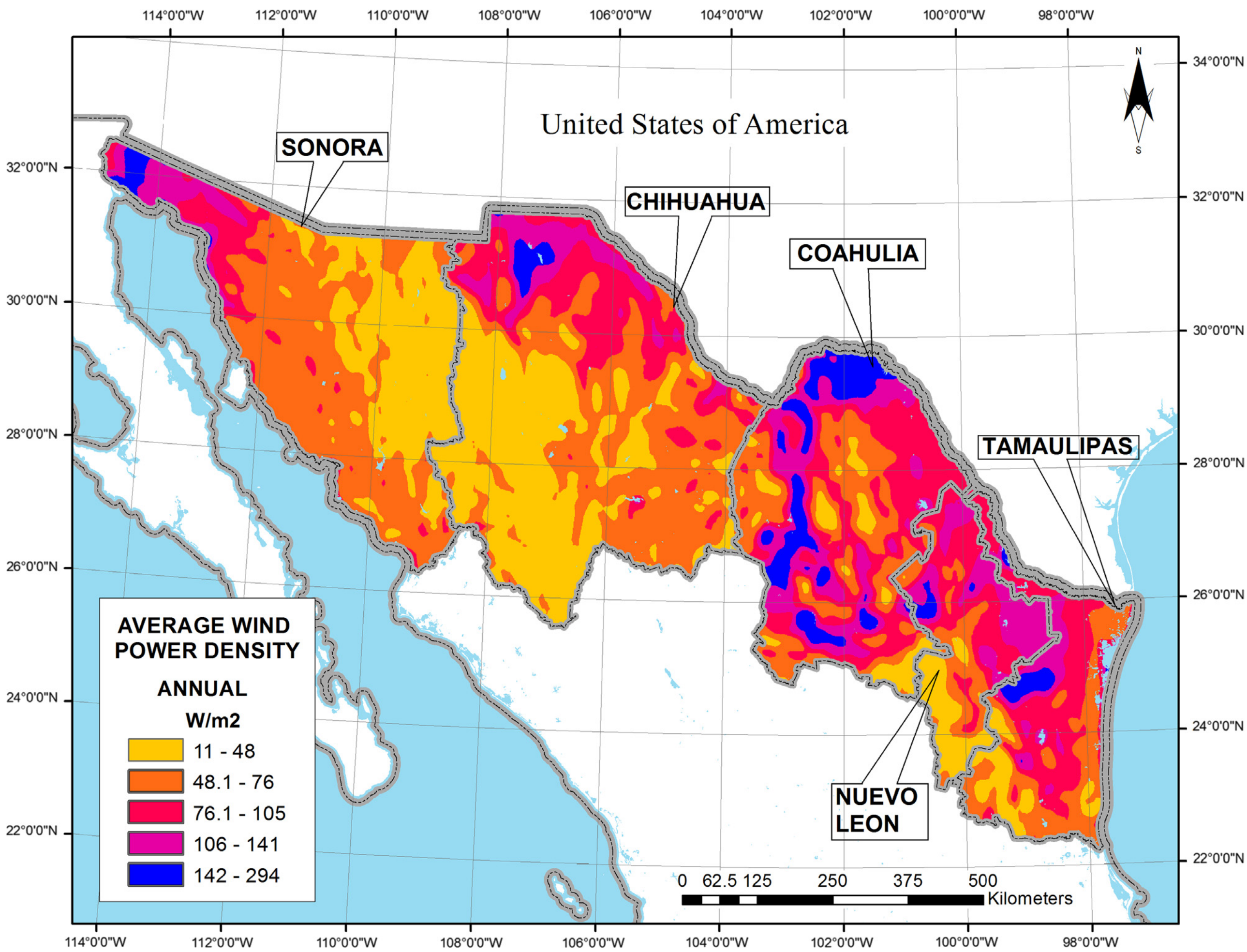

Fig. 16. Northern Mexico annual WPD.

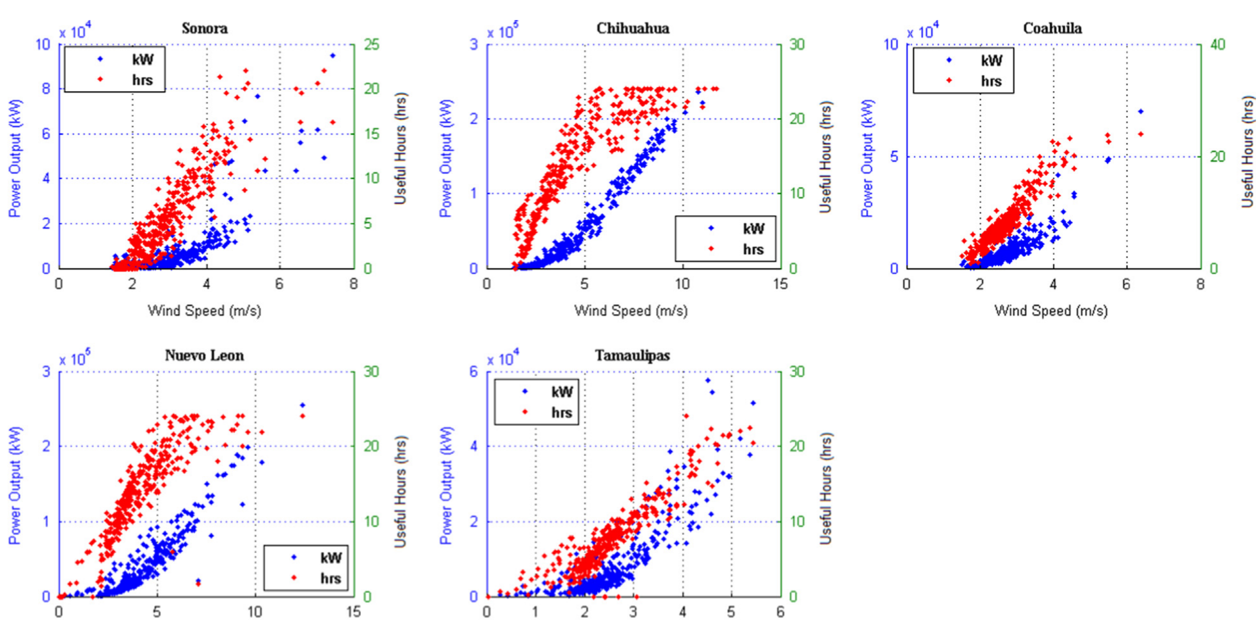

Fig. 17. Power Output (kW) vs. Useful Hours (hrs).

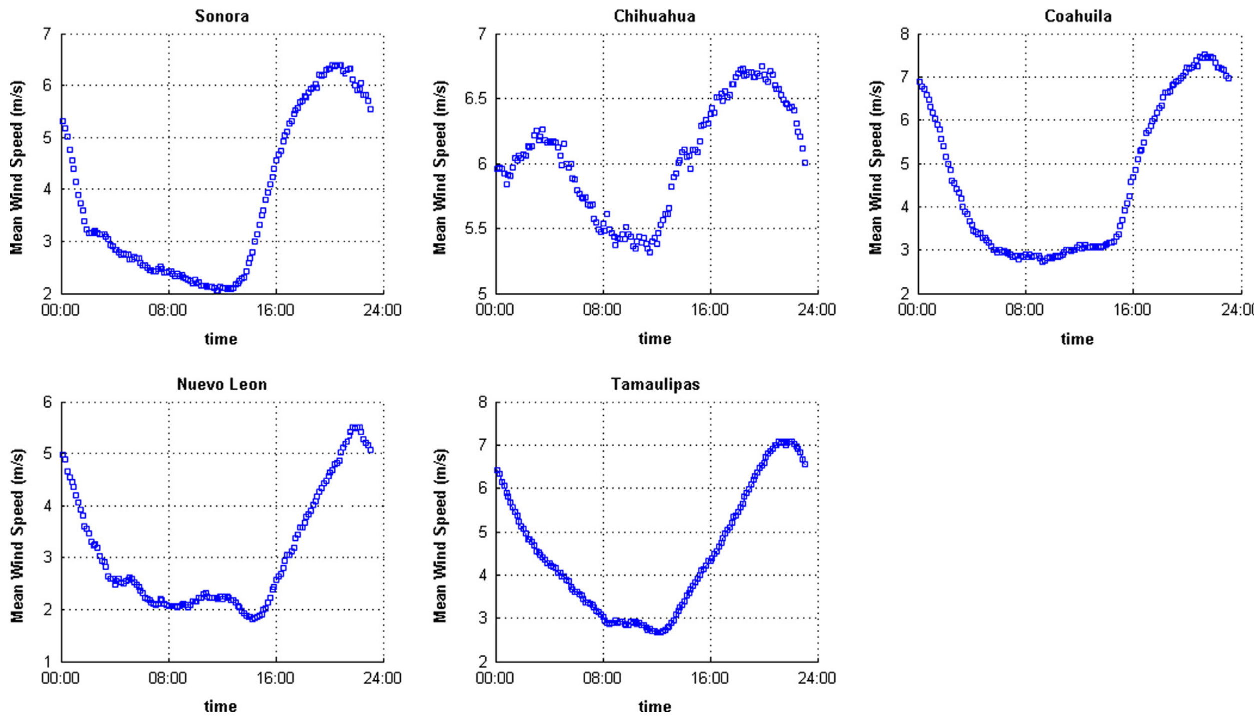

Fig. 18. Daily pattern of wind speed in the northern states of Mexico.

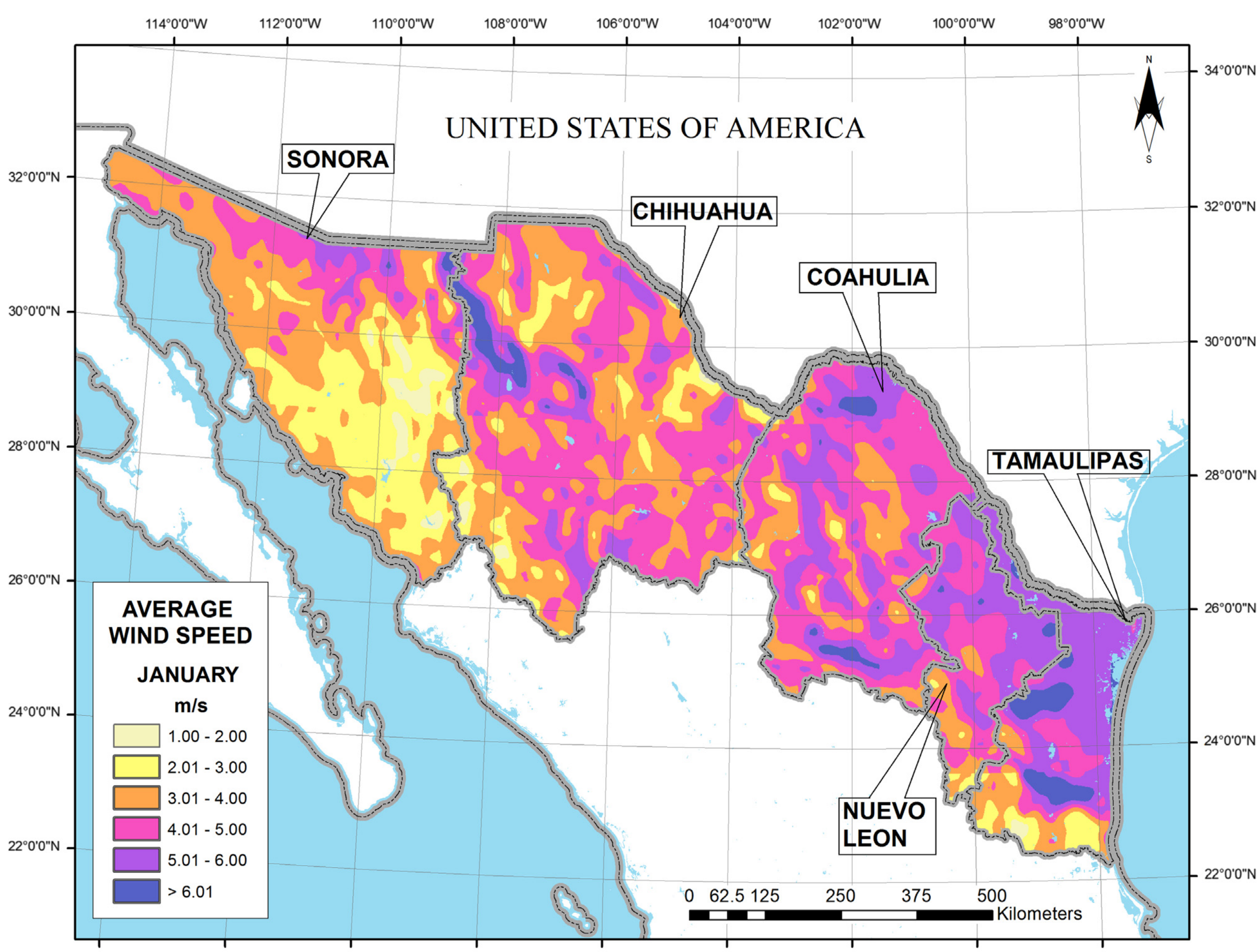

Fig. 19. January, average wind resource map.

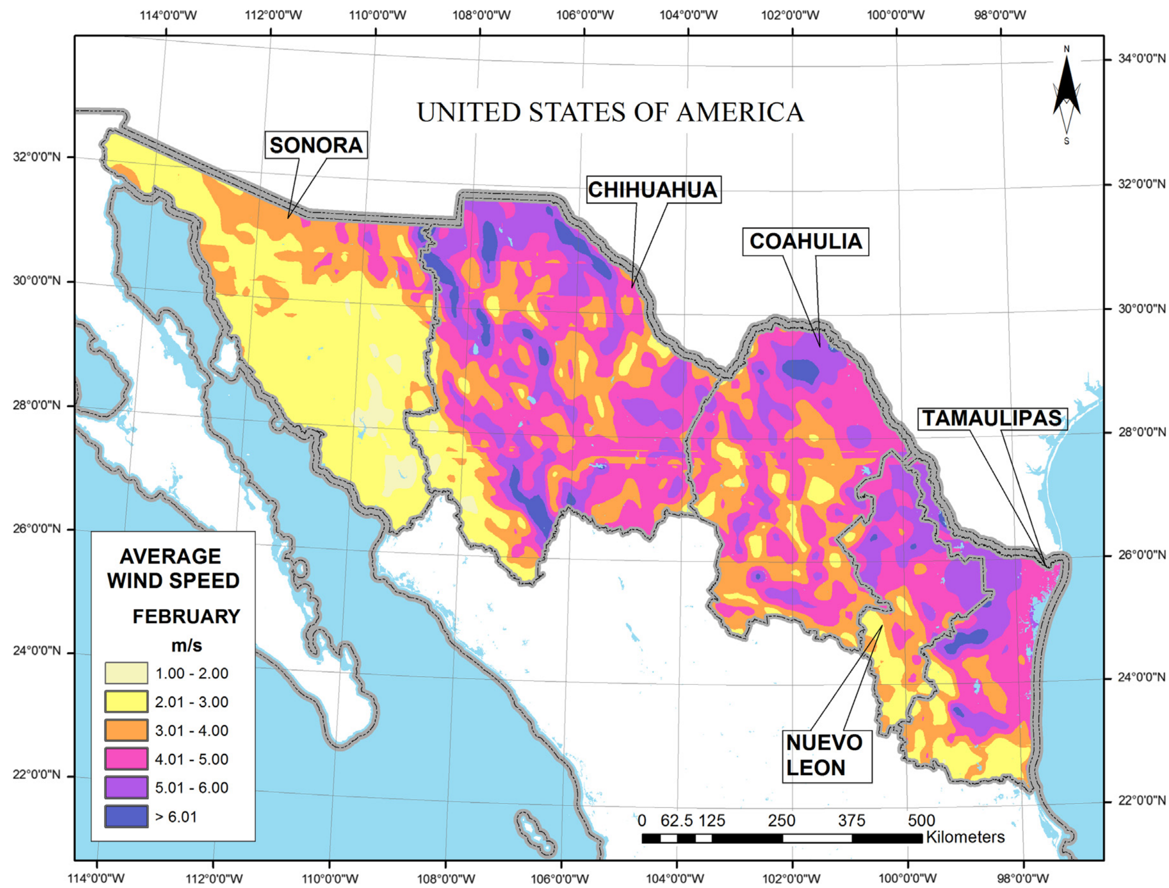

Fig. 20. February, average wind resource map.

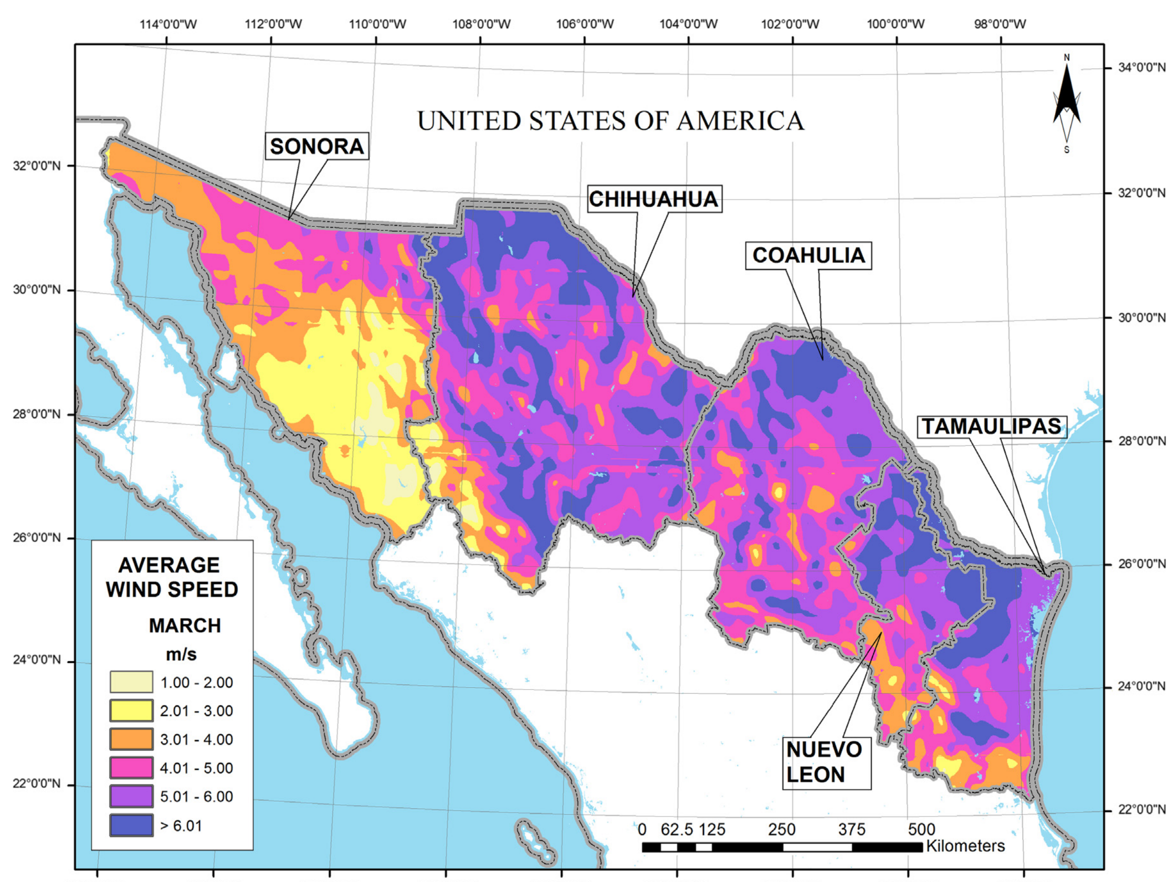

Fig. 21. March, average wind resource map.

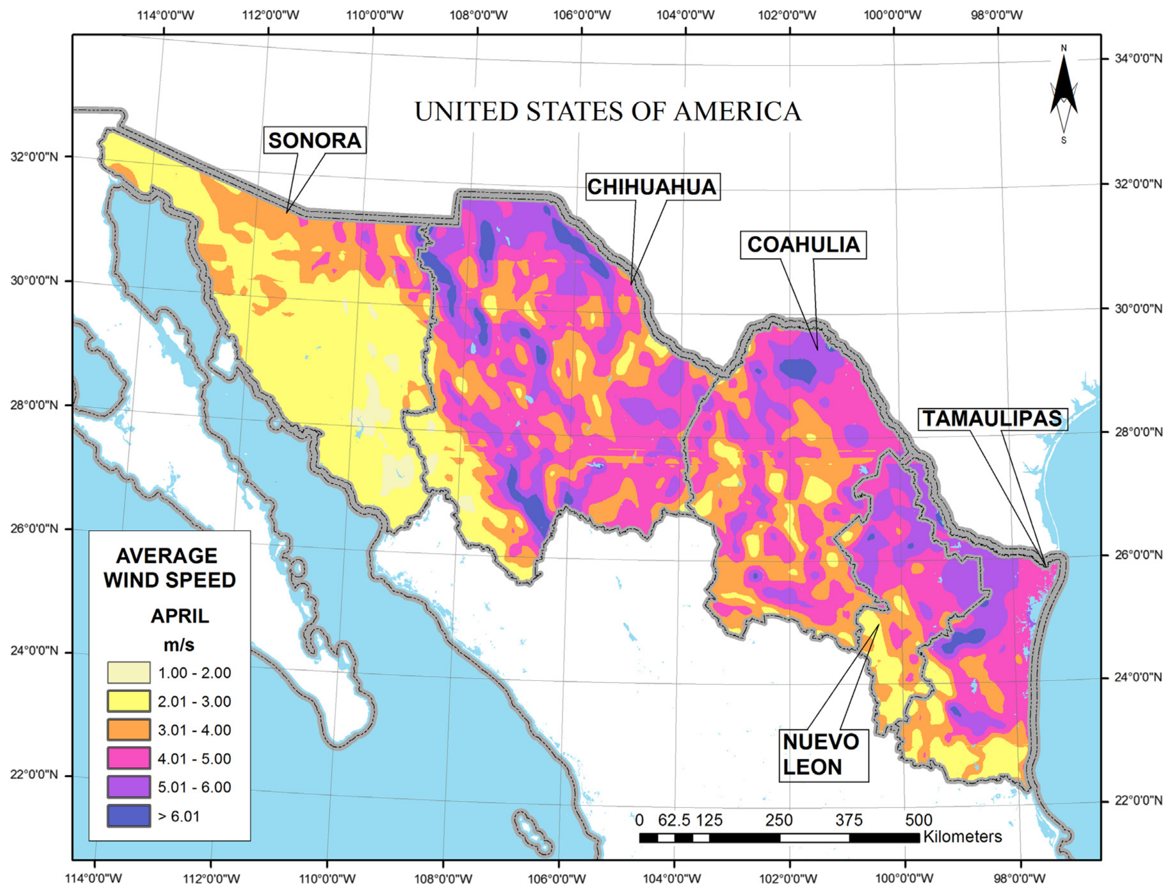

Fig. 22. April, average wind resource map.

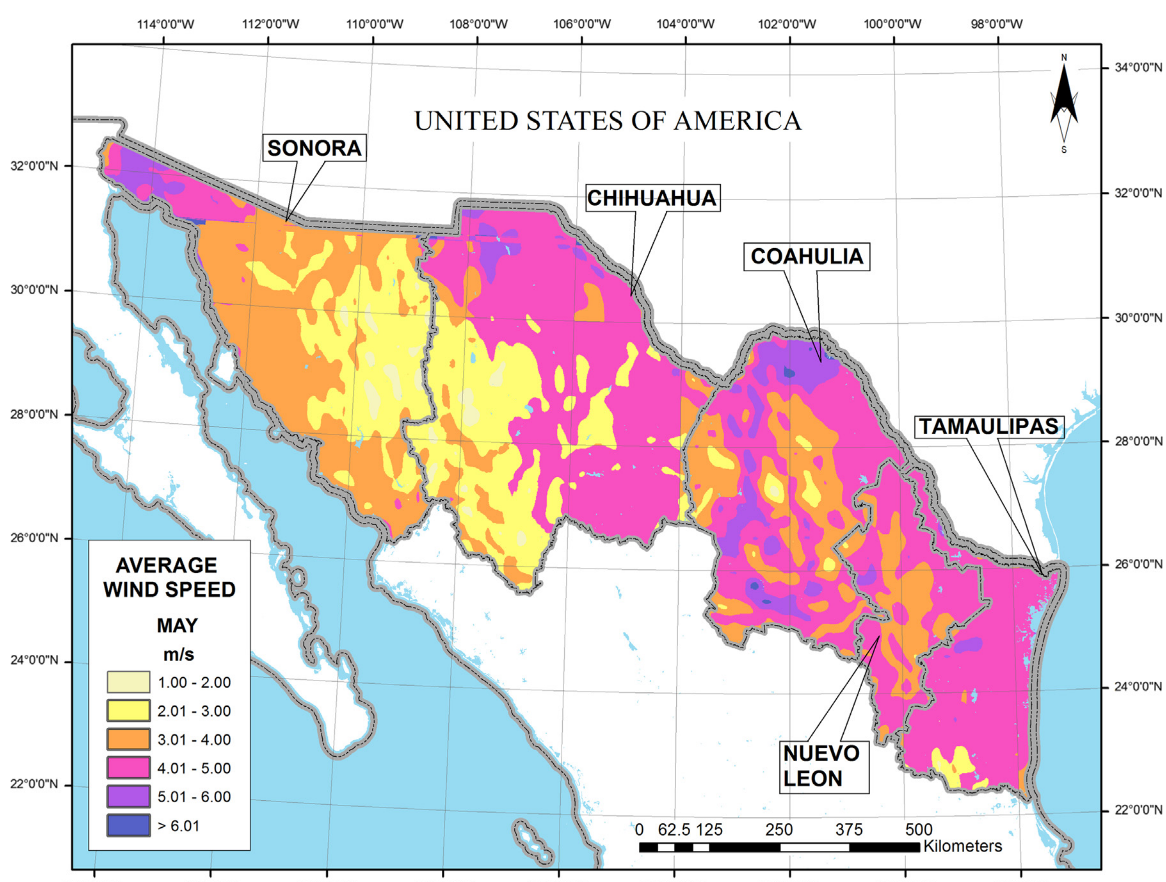

Fig. 23. May, average wind resource map.

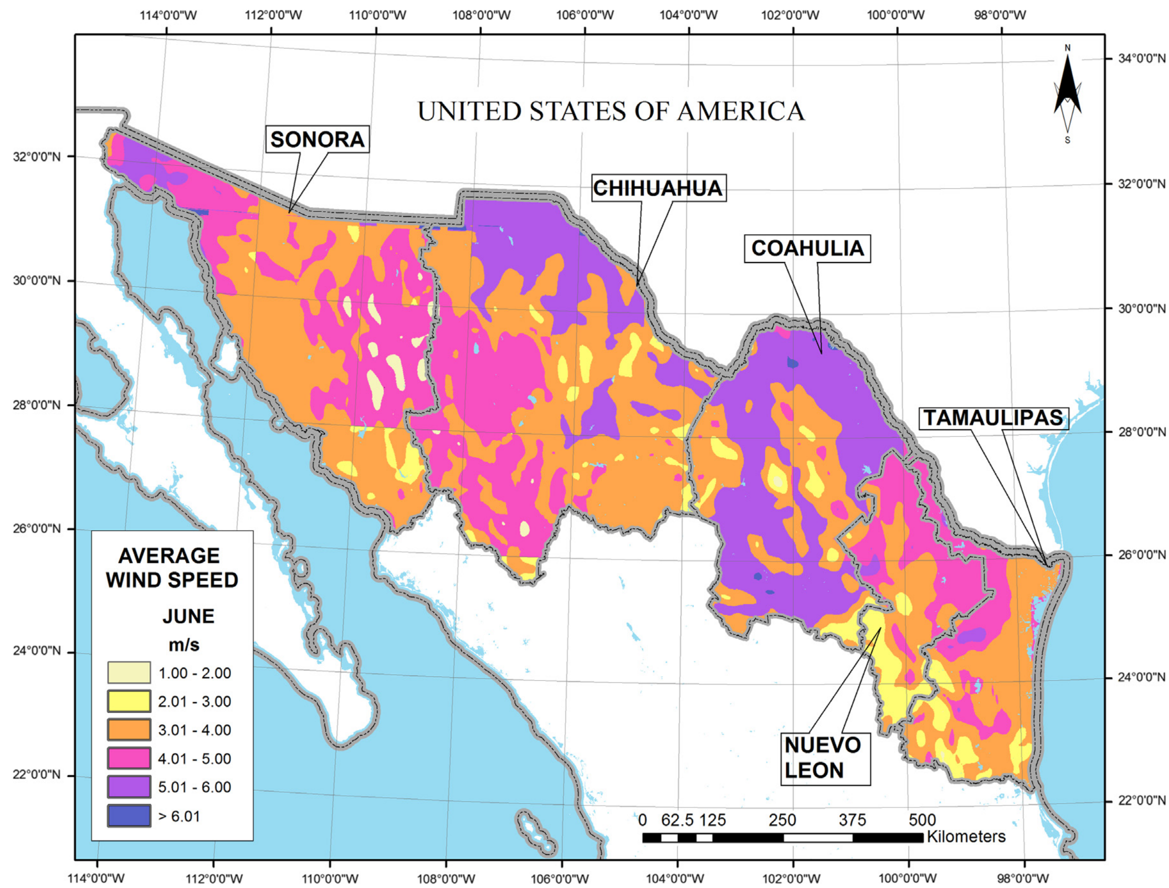

Fig. 24. June, average wind resource map.

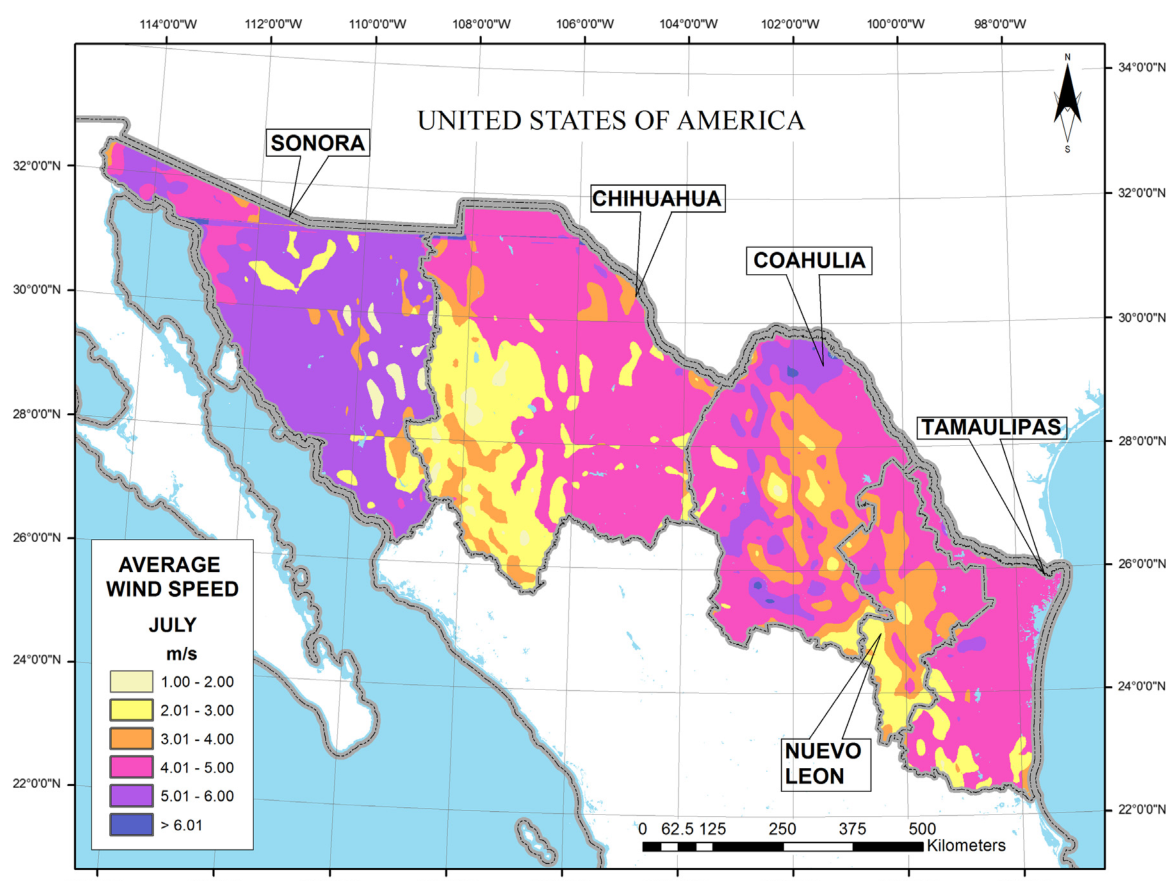

Fig. 25. July, average wind resource map.

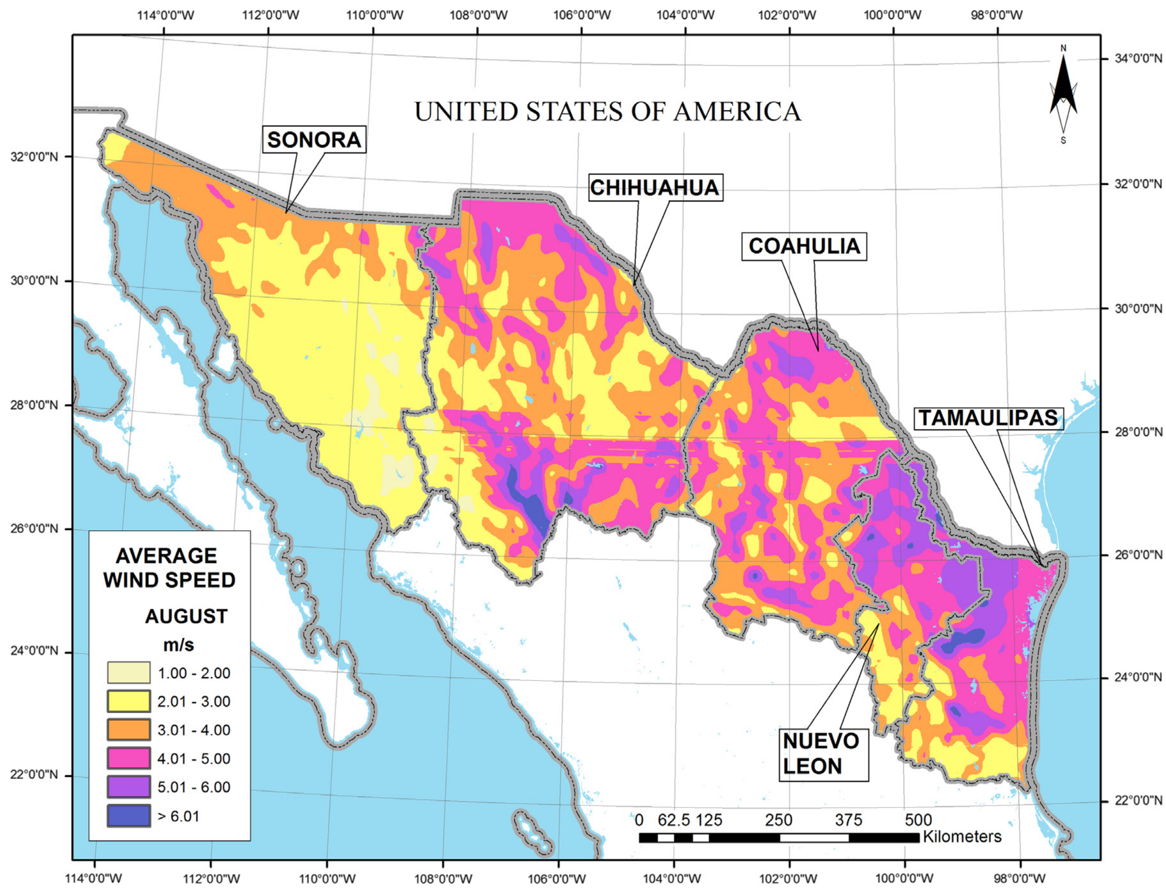

Fig. 26. August, average wind resource map.

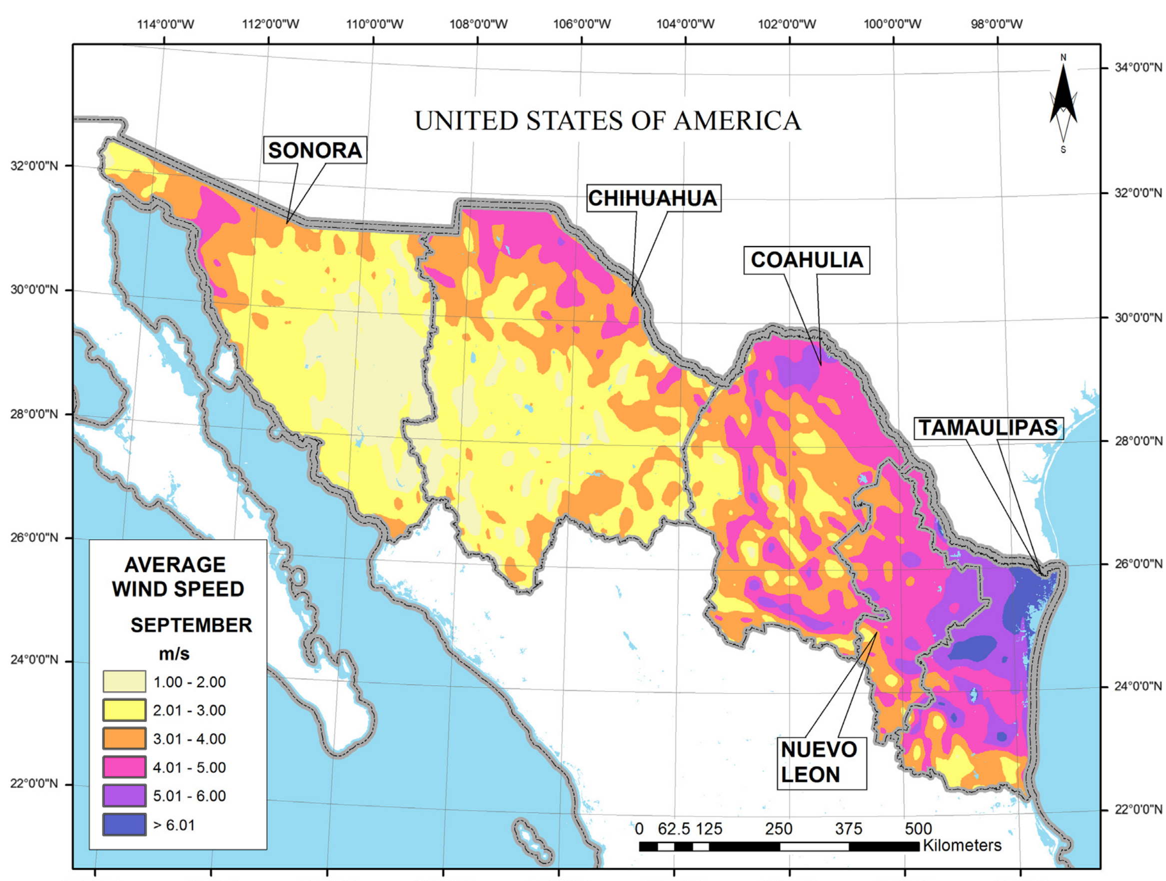

Fig. 27. September, average wind resource map.

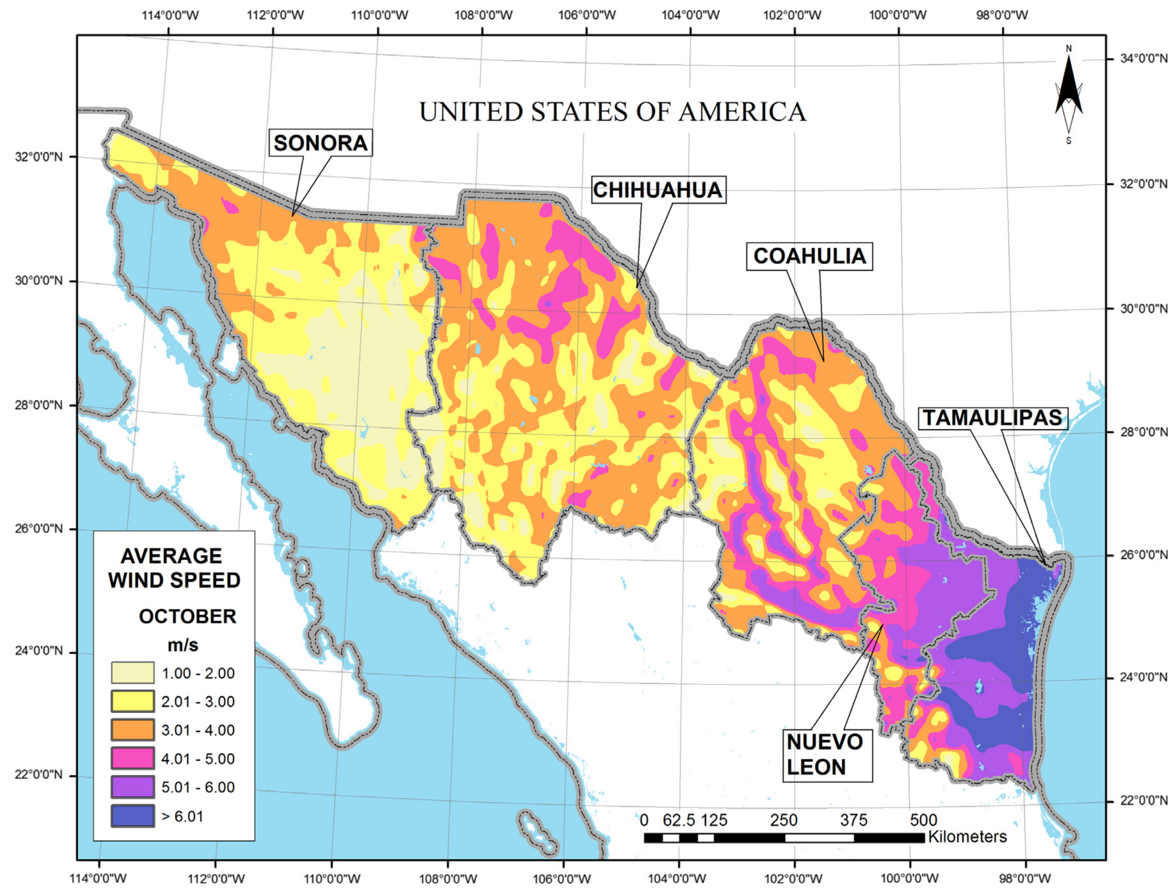

Fig. 28. October, average wind resource map.

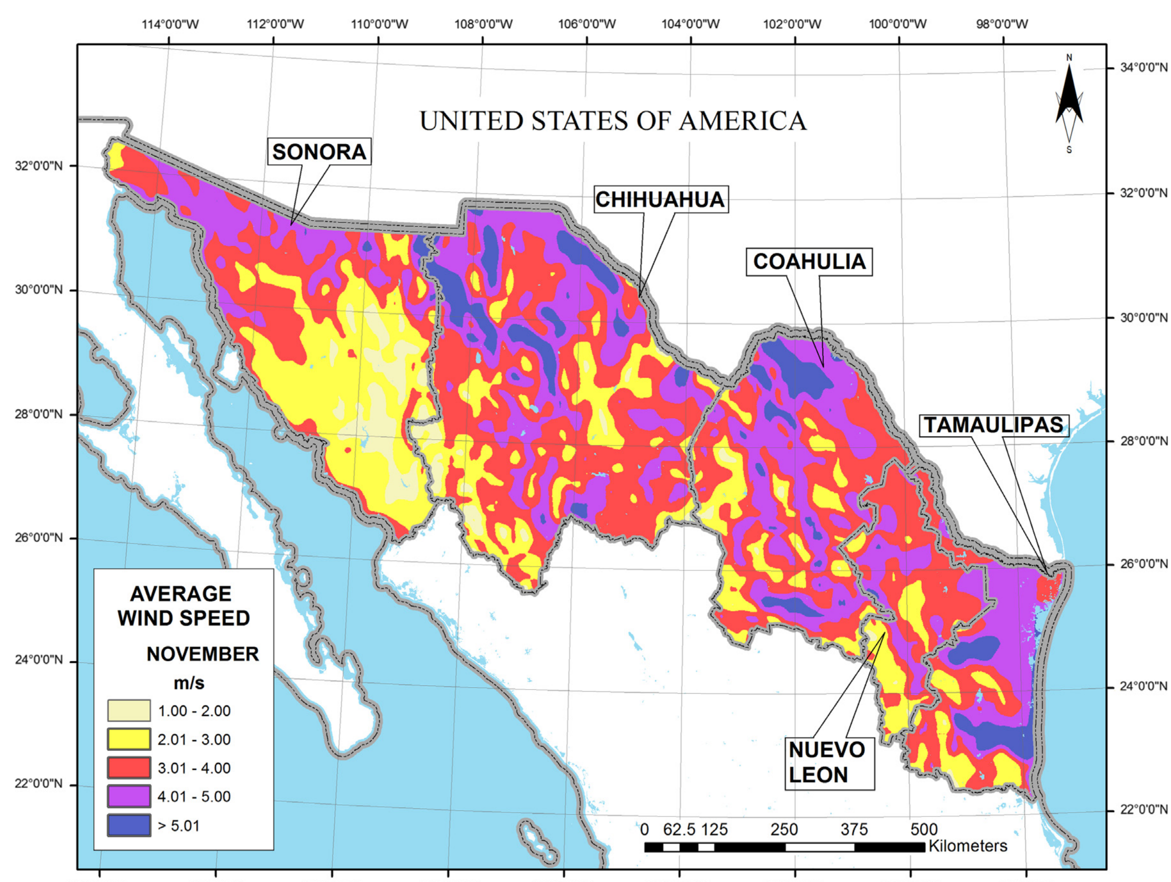

Fig. 29. November, average wind resource map.

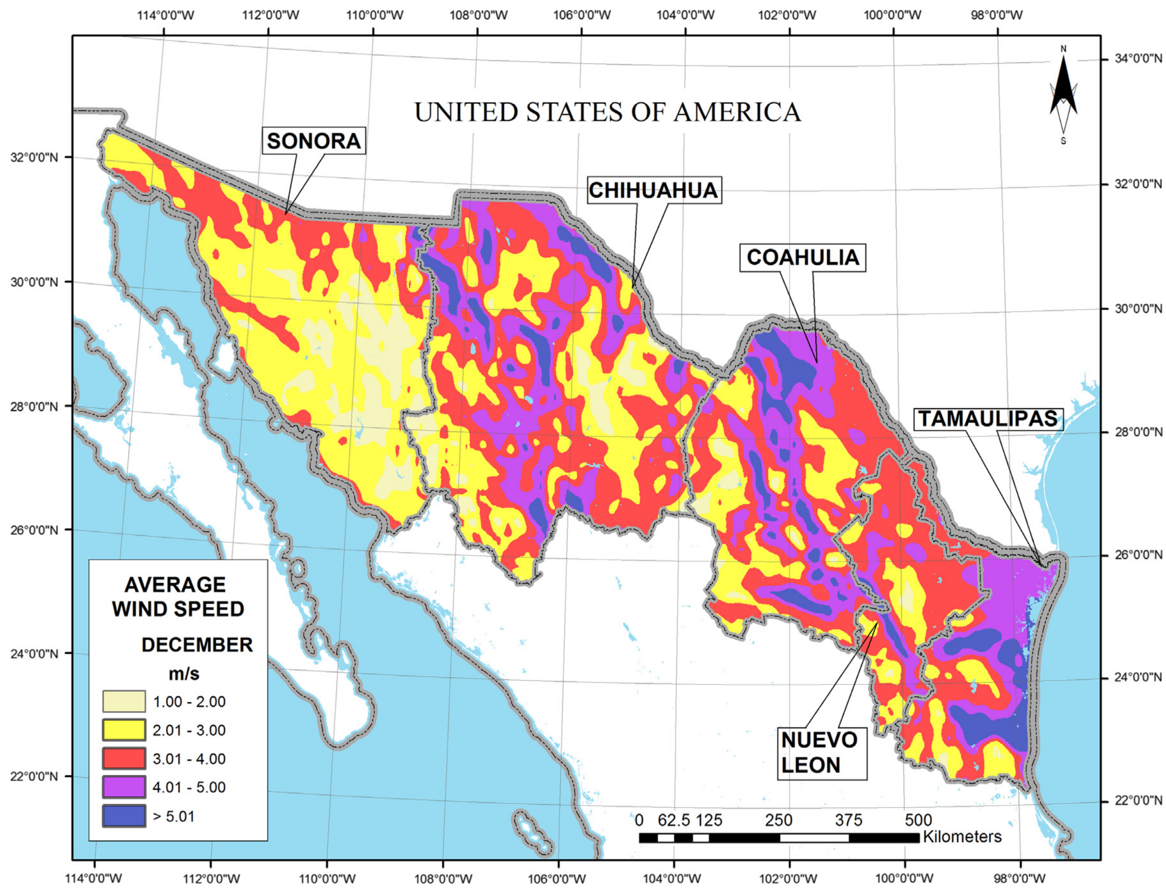

Fig. 30. December, average wind resource map.

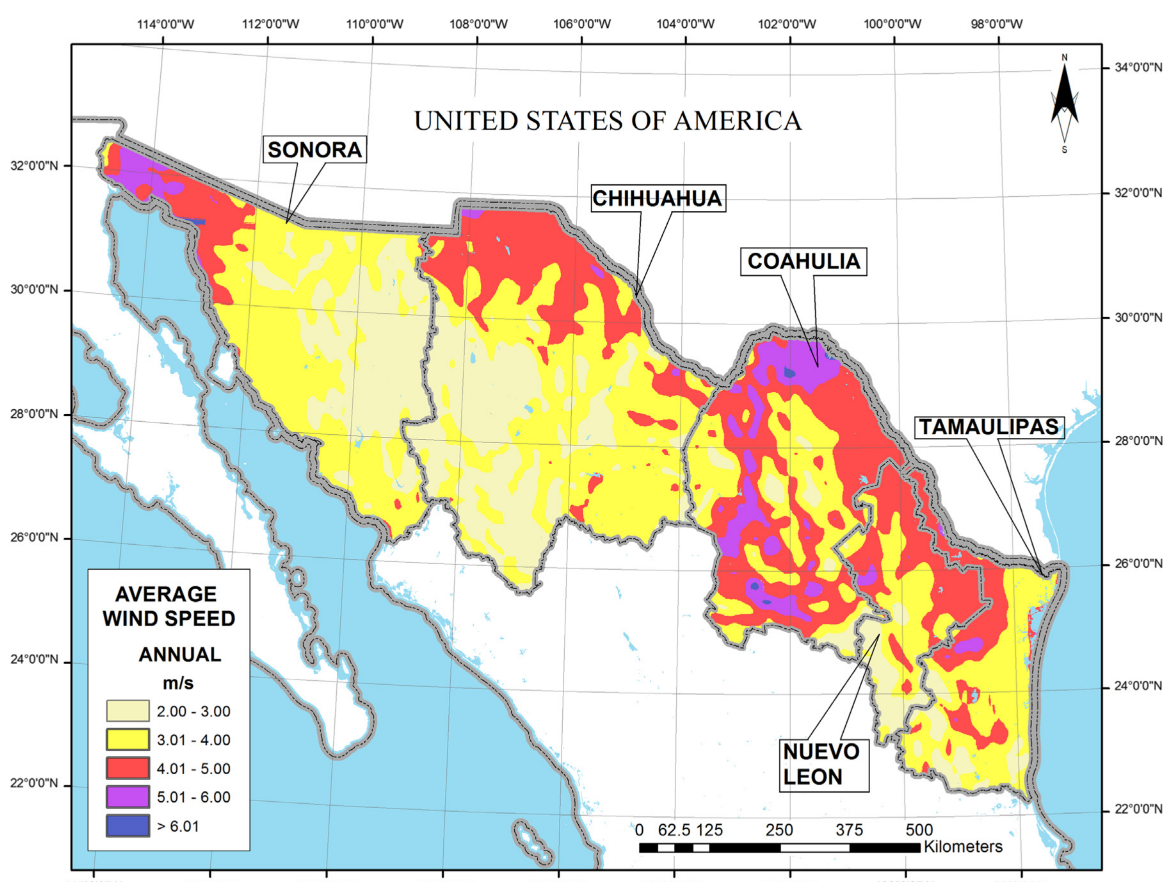

Fig. 31. Annual average wind resource map.

complete evaluation of the entire country's wind potential and does not provide tax incentives to attract investors to build wind farms; as a result, the Mexican government has proposed structural reforms, including energy reform, which includes investment in renewable energy in the country.

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